Mr Tompkins Learns the Facts of Life

by G. GAMOW

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This time Mr Tompkins, the hero of two earlier books by Professor Gamow, turns his attention to biology, and as usual he is lucky in meeting the right guides. First he is injected into himself, and travels extensively. He discovers something of the functions of his cells and bloodstream, and he finds (with more mingled feelings) those forms of almost independent life that exist in myriads within him.

Some of the things which happen to his breakfast nearly happen to him.

He meets a motherly gene of his who introduces him to other departments of his collective existence. Not only are his personal characteristics explained; he also begins to understand enzymology and cell-division. Side-stepping a shower of cosmic ray particles, he survives to meet The Maniac, a proud but discursive electronic brain who explains his workings, and suggests that Mr Tompkins, to understand *his*, should go into his own brain. He does, and finds a Russian scientist; has his foot stamped on, sees himself react and has explained to him the composition and broad principles of the brain and nervous system. He asks 'what is it that makes my multitude of cells *me*?' and gets a searching answer in the form of a parable.

Finally he hears a lecture given for him and people like him by the Professor; it faces the bigger questions that these adventures had pointed to: what is life; how did it start? How do certain forms of energy (atoms) combined into complex molecules become living cells? In his answer the Professor describes the enormous conversions of energy constantly taking place in our world. He explains that a fundamental characteristic of life is 'negative entropy' or the degree of 'lack of tendency to disorder' in matter. He shows how plants acquire it by converting the sun's light into the principle of celi-construction. And he sums up, in terms that any ordinary thinking person can grasp, the present state of biological knowledge and the answers it can give to some of the questions about ourselves and about life that have always bothered our minds.

The picture on the front of the jacket shows Mr Tompkins considering his X-chromosome. The lady is the gene who is responsible for his curiosity.

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GEORGE GAMOW

Professor of Theoretical Physics
George Washington University

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AUTHOR

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Dedicated to R. W. Wood
Who said that he would and he could
Tell birds from the flowers
And bring readers of ours
To the same semi-jocular mood.

Preface

WHEN the desperate Professor Moriarty met Mr Sherlock Holmes on a narrow mountain pass, and after a short struggle they both tumbled head-over-heels down the precipice, the books seemed to have been closed on the famous British detective. But, lo and behold, he appeared again in the *Return of Sherlock Holmes*, simply because his renowned author could not bear that his hero should be dead for ever.

The return of Mr Tompkins, who in the last volume had given his wife, Maud, a solemn promise to stay away from physics, can be explained in much the same way. Indeed, it can be done even without breaking any promises, since the subject of the present volume is not physics but biology.

The presentation follows the general pattern of previous reports on Mr Tompkins's adventures, and consists of three dreams and a lecture by the Professor.

G. GAMOW

Num-ti-jah Lodge,
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G. G.

May 1952

First Dream

THROUGH THE BLOOD-STREAM

The large waiting-room of the New Memorial Hospital was cool and comfortable. The patients were sitting in somewhat strained poses, waiting for their turn to be called for inspection. Some of them were trying to distract their thoughts by glancing through magazines, others were just staring blankly into space. Once in a while a stretcher rolled past, pushed by a white-clad attendant; everybody's eyes automatically followed the procession until it disappeared at the far end of the corridor.

Mr Tompkins picked up the latest issue of *The New Yorker*, but the subtle humour of the cartoons, which he always enjoyed so much, did not seem to affect him now. Yesterday he had felt quite all right and full of life. But this morning, during breakfast, he had glanced through a newspaper account of a lecture on cancer. The article described in vivid words how the usually regular and well-coordinated processes of cell division in living tissue can sometimes get out of hand, producing ugly malignant growths, and leading ultimately to the complete destruction of the organism. The author had compared these destructive tendencies of certain aggressive cell groups, which appear now and then within the peaceful commonwealth of normal cells constituting a living organism, with similar phenomena in the field of sociology and world politics, and suggested that in both cases the only cure known at present is the use of the scalpel or the sword.

"Sure," agreed Mr Tompkins, "to hell with all this appeasement business. *Si vis pacem, para bellum*!"

But when he got to the bank, thoughts about the grim possibility of aggressive cell division just would not leave his mind, and all the while, as he cashed cheques, he felt that something unusual was going on in the organized community of cells which he called his body. His head was

heavy, his respiratory organs seemed to work under unusual strain, and he felt an ache in all his joints.

As he had also completely lost his appetite, he decided to make use of the lunch hour for a visit to the dispensary of a large city hospital, which was fortunately just round the corner. He wanted to make sure that no aggressive cell groups were operating in *his* body. There was a long waiting line, so he picked up a magazine from the central table, and settled comfortably into the last vacant arm-chair. He felt quite relaxed now, and a few minutes later the magazine fell softly on to the marble floor at his foot.

* * * * *

Suddenly all the people in the waiting-room straightened in their seats, and turned their heads towards a tall man in a snow-white laboratory gown, who had just walked in through the door of an adjacent office. Mr Tompkins knew this man very well indeed, through photographs which appeared now and then in the city's newspapers. It was the famous Doctor Streets, the world-renowned authority on abnormal cell growth. Noticing Mr Tompkins, who was almost hidden from sight by an enormously fat lady sitting next to him, Doctor Streets rushed towards him with wide-open arms.

"Oh, my dear Mr Tompkins, what in the world could have brought you here?"

This was very strange indeed, since, though Mr Tompkins might well know of this famous figure of the medical world, Dr Streets had no reason whatsoever to know Mr Tompkins.

"I came here, Sir," said Mr Tompkins, feeling the eyes of all the patients in the waiting-room concentrating on him, "to check the mitosis rates in my cells, and to find out if there is any neoplasm formation or any danger of metastasis." (He thought that by using this scientific language he would have some excuse for being inspected ahead of all the other patients.)

"Oh yes, of course", said Doctor Streets, becoming suddenly quite serious. "We can get inside your body and have a quick look round at

various cell communities to be sure they are behaving in the proper way. It shouldn't take too much time, provided one knows what to look for."

"You mean," said Mr Tompkins with a chill running down his spine, "you want to open me up?"

"Oh, no," said Doctor Streets soothingly, "it won't be necessary unless, of course, we find something wrong. I am just going to inject you into your own blood-stream, so that you can see for yourself the various cell colonies from which you are formed. The round trip through your main circulatory system takes not more than half a minute but, of course, since we shall have to change our linear dimensions, the time scale will change too, and we shall be able to make the inspection in quite a leisurely way."

As he spoke, Doctor Streets put his hand into a pocket of his white gown and, pulling out a large hypodermic syringe, pointed its long shiny needle towards Mr Tompkins. There was a violent feeling of suction and for a moment Mr Tompkins felt just as if he were a camel trying to squeeze itself through the needle's eye. Then something pinched his arm above the elbow, the suction turned into pressure, and Mr Tompkins was forcibly ejected into a rapidly flowing mass of some slightly yellowish transparent fluid. For a moment he felt like an inexperienced diver, who had jumped by mistake from a high diving board, and was making

Fig. 1. As if he were a camel trying to squeeze itself through the needle's eye

desperate motions with his arms and legs to come to the surface. But, although this did not bring him anywhere, he did not seem to feel any lack of air, and his lungs seemed to function quite normally.

"What a dirty trick," exclaimed Mr Tompkins; "he must have turned me into a fish!"

"You don't need to be a fish", said a quiet voice near him, "to be able to breathe inside your own blood-stream. After all, it carries all the oxygen supply needed for the respiration of your body cells. But if you feel uncomfortable floating in the plasma, why don't you climb up on one of the erythrocytes and have some rest. They are just as comfortable for travel as the proverbial flying carpet."

It is only now that Mr Tompkins noticed a large number of lens- or bean-shaped bodies floating in the fluid stream. They were about three feet thick, some twenty feet in diameter, and seemed to be upholstered with bright red velvet.* Climbing up on one of them with the help of the doctor, Mr Tompkins felt that his miseries were over.

"Aren't these erythrocytes, as you call them, simply what are known as red blood cells?" he asked, stretching out on the soft velvety surface.

"Exactly so," was the answer, "in fact, *erythros* means 'red' in Greek. The material which gives them that bright red colour is known as haemoglobin and is a complicated chemical substance possessing great affinity for oxygen. When the blood-stream passes through the lungs, these red blood cells absorb large amounts of oxygen and carry it along to various cell-colonies in the body. In fact, although erythrocytes occupy less than fifty per cent of the volume of the blood fluid, they can absorb seventy-five times more oxygen than can possibly be dissolved in the plasma itself."

"Must be a tricky substance", said Mr Tompkins thoughtfully.

"So it is", agreed Doctor Streets. "And, as a matter of fact, bio-

* *Editor's note:* Mr Tompkins was colour-blind, but from his early childhood he had learned to guess what is red and what is green. In this case he was sure that it was red haemoglobin and not green chlorophyll, since he was inside himself and not inside a plant.

chemists are still working hard to get its exact composition. So far, we have been able to untangle only one small part of this complicated molecule, a part known as haematin. If you use this lens, you can see how complicated its structure actually is."

"You mean I can see the separate atoms forming the molecule?" asked Mr Tompkins with surprise.

"Sure you can. At our present scale you are just about two microns tall. That means that the atoms will look to you like little spheres a few tenths of a millimeter in diameter. A simple pocket-lens would be enough to see the structure quite easily. Just look at those little pimples covering the surface you are sitting on."

Taking the lens from the Doctor's hand, and stretching out on his stomach, Mr Tompkins concentrated his attention on a tight group of seventy-seven atoms forming a haematin molecule. It was a symmetrical structure built around a heavy atom of iron located in the very centre. The iron atom was surrounded by a group of four nitrogens, and twenty carbons. Outside were attached hydrocarbon and carbohydrate groups sticking out in all directions, like the tentacles of an octopus. Caught in these tentacles like flies in a spider's web were numbers of oxygen molecules absorbed by the haematin.

"It's funny," said Mr Tompkins, straining his eyes to see all the details, "I can see quite clearly the structure of the haematin molecule itself, but I can't make out anything of the larger body to which it is apparently attached."

"That is simply because you can't see in your dreams the things which have not yet been cleared up by regular scientific research", explained Doctor Streets. "The structure of haematin is known in detail through the work of the German biochemist, Hans Fischer, whereas the structure of the much larger protein molecule to which it is attached still represents one of the unsolved problems of the science of biology. I wouldn't mind having a look at it myself if my pocket-lens would show more than is known to science today."

The two men were so involved in their conversation that they did not notice that the broad stream through which they were previously floating, had narrowed into a small channel, and that their erythrocyte was gliding most of the time along its slippery semi-transparent walls.

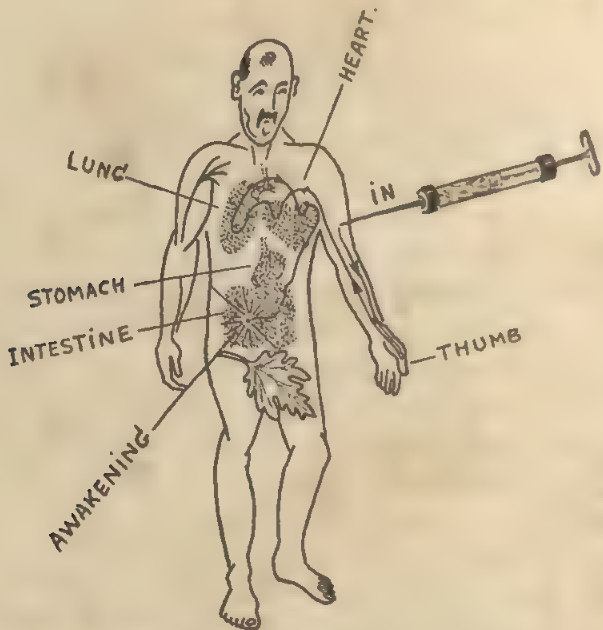


Fig. 2. Map of Mr Tompkins's travels inside himself

"Here we are!" exclaimed Doctor Streets, looking around. "We have entered one of the small capillaries supplying the blood to the thumb of your left hand. These large lumps of protoplasm lining the walls of our capillary channel are the living cells of your own flesh."

"Oh!" said Mr Tompkins who had already seen microphotographs of cellular structure, "they look exactly as they should. And, I suppose, the darkish bodies near their centres are the *nuclei*?"

"Right", replied the Doctor. "And, speaking of cancer, you notice

that these particular cells are quite normal. Cancerous cells are characterized by a special growth pattern, and in some cases by abnormally large nuclei, and can be easily distinguished under the microscope from normal healthy cells. The trouble is, of course, that in order to diagnose cancer in its early stages, one would have to examine millions of cells to be absolutely sure. But I hope that we shall soon be able to develop some methods which would permit us to do so in a quick and inexpensive way."

"I see," said Mr Tompkins, who had begun to feel a little short of breath, "I hope you will have such a method soon. But it seems a little stuffy here."

"Sure it does", retorted the Doctor. "After all, the blood-stream with which we are travelling comes here to give away its oxygen content to the cells, and to take carbon dioxide and carry it away from your body. Watch how the oxygen molecules are getting detached from the body of our erythrocyte and sticking to the walls of the capillary. They will then diffuse through these walls into the lymph (the liquid surrounding the individual cell), and then into the cells themselves. At the same time, the carbon dioxide accumulated in the cells is draining outwards into the blood-stream where it is partly dissolved in the plasma, and partly attached to the molecules of the haemoglobin. So our trip back to the lungs is not going to be pleasant."

"I should say so", grumbled Mr Tompkins, feeling his lungs nearly bursting. "Isn't it silly that I must almost suffocate in order to keep my own thumb breathing?"

He certainly did not feel too good, and black spots were floating before his eyes.

"Must be cellular nuclei", thought Mr Tompkins. "Oh, no! It looks more like heads with sailors' caps on. Am I joining the Navy, or what?"

"Two hundred fathoms," said a husky voice from nowhere, "and still going down. D—— these jammed valves!"

"I hope they know about it at the Base", said another voice. "They'll surely do something about it."

"Oh yeah!" screamed somebody in semi-hysterics. "No brother, there's no way out of Davy Jones's locker!"

Suddenly the body of the submarine was whirled round violently as if caught in a giant whirlpool. The people and the instruments were thrown about all through its narrow interior, and Mr Tompkins found himself clinging to the base of the periscope. For a moment he saw the face of the Doctor, a chalk-white face....

"Hold on!" whispered the Doctor, "we have just entered the *right ventricle* and are heading into the *pulmonary artery*. There will soon be enough air for everybody!"

When Mr Tompkins again recovered consciousness, the air, or rather the plasma, was indeed quite clear. He was lying on the same erythrocyte tightly embracing the Doctor's leg. Their erythrocyte was again floating smoothly through a rather narrow channel but there were no cells crowding the space on the other side of its transparent walls. On the contrary, it seemed quite empty except for swarms of what Mr Tompkins first thought to be little flies or fleas, dashing through it in all directions.

"Atmospheric air", said Dr Streets pointing with his long finger.

"You mean we are out of my system?" asked Mr Tompkins hopefully.

"Oh, no," said the Doctor, "we are still in your circulatory system, but we are now passing through one of the capillaries of your lung, to get rid of the carbon dioxide, and take in a new supply of oxygen. The free space across the wall of the capillary is called an *alveolus*, and is just one of the air pockets, or bays, which line the inside surface of the lung. Each time you breathe, the lung and all its alveoli are filled by the fresh air from the outside so that venous blood can get its new supply of oxygen."

"You mean that these tiny rushing insects are actually air molecules?" exclaimed Mr Tompkins.

"That's it. But remember that in our present scale, which is roughly one in one million, simple molecules like those of oxygen or nitrogen are about one tenth of a millimeter in diameter. No wonder you mixed them up with fleas, especially considering their fast, dashing movements. See how

many of them get through the walls of the capillary and attach themselves to the red blood corpuscles. By the time the blood finishes its passage through the lungs, and enters into the *aorta* it is ready again for the new trip across your body."

"I don't think I should like to make that journey again", said Mr Tompkins, who had not yet recovered from his unpleasant experience.

"But you should!" retorted the Doctor. "You haven't seen much yet, in fact you were delirious throughout most of the long trip from your thumb to the lungs. Besides I haven't yet had a chance to look into the question about which you came to me, and to diagnose your condition."

"All right," said Mr Tompkins reluctantly, "but perhaps we can get hold of an auxiliary oxygen tank."

"We can do better than that," said the doctor, "as soon as conditions become really uncomfortable we'll simply get out of your system. But you'd better get ready for a rough ride now, as we are just going to enter your left heart."

"What do you mean: left heart?" exclaimed Mr Tompkins, baffled. "I thought the heart is always on the left."

"That is correct, and I should rather have said, left half of your heart. You probably do not know that the human heart, which is essentially a pump driving the blood through the body, is actually a double pump. The right half of the heart pumps the blood from the body into the lungs, whereas the left half pumps it from the lungs back into the body. Both pumps, complete with valves and so on, are quite independent, except that both are driven by the same muscles. Now hold on!"

Their erythrocyte was now behaving very much like a canoe riding the rapids of the Colorado River, and Mr Tompkins had quite a difficult time trying not to be thrown off into the swirling plasma. They rushed through a narrow opening into the left *auricle* (the entrance chamber of the heart) and then through another valve into the left ventricle itself. A second later the heart contracted, and their erythrocyte was forced out again through the exhaust valve of the heart pump.

"Well," said the doctor making himself comfortable on the soft velvety surface, "now we can have a long chat about things. Is there anything in particular you would like to know?"

"I would like to know first of all", said Mr Tompkins, "whether or not this thing we are riding on is alive?"

"It's a difficult question", said Dr Streets. "The answer is probably yes, but with some reservations. The fact is that red blood corpuscles are constantly being born; they live through their life, and finally they die when they are three to four months old. The breeding place of erythrocytes is the red marrow of the bones, where they are produced by the steady regular division of special cells, known as erythroblasts. But when they get out into the blood-stream their nuclei decay and a cell without the nucleus is only half alive. In particular, they completely lose the ability to reproduce themselves, since cell-division is a process governed completely by the nucleus. All they can do now is just to carry the loads of oxygen from the lungs to the body cells, and the loads of carbon dioxide from the body cells to the lungs, thus supporting the life of the entire cellular colony."

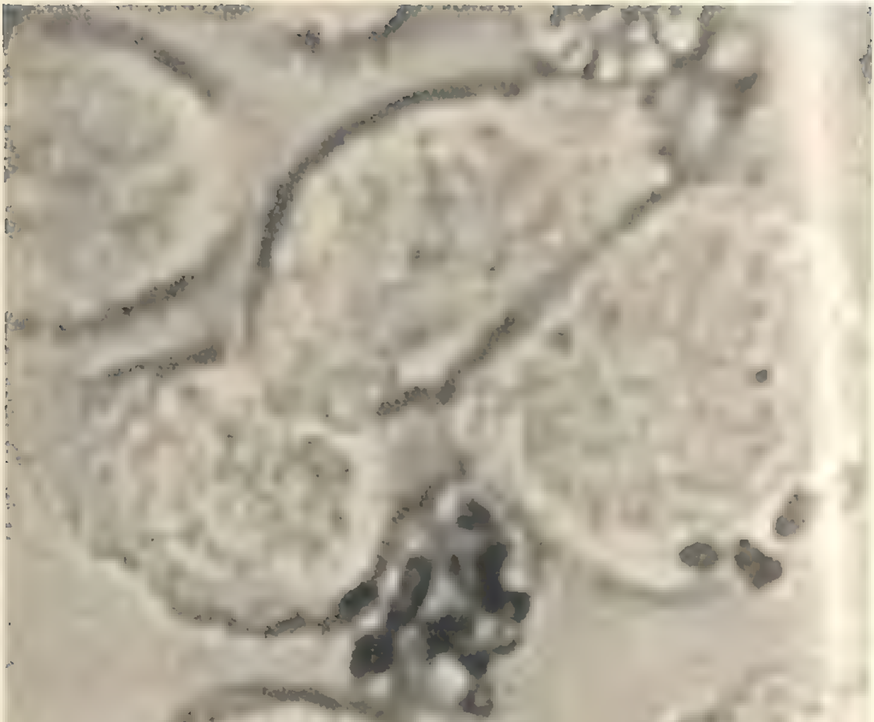
"Like oxen or mules", inserted Mr Tompkins.

"Yes, very much so," smiled Dr Streets, "and as load-carriers they are, of course, completely indispensable."

"Are they deprived of their reproductive power", continued Mr Tompkins, "so that their sex instincts do not interfere with their work?"

"Maybe, maybe," said the Doctor reflectively, "although, of course, there are many cases (the frog's blood for example) where erythrocytes retain their nuclei all the time while in circulation. Again, in the case of a man who for some reason or other has lost a lot of blood, immature erythroblasts are poured into the blood-stream to support the dwindling cargo traffic. So it really doesn't make much difference. When erythrocytes die they are disintegrated in your liver and spleen, and their remains are removed through the urine."

"But what about the *white blood cells*?" asked Mr Tompkins. "Do they carry some special load through my body?"



I. *Several phagocytes had cornered a bunch of bacteria*

(*Courtesy of Dr William Barry Wood, Jr., Washington University, St Louis, Missouri*)

"Oh no," replied Dr Streets, "white blood cells, or *leucocytes* have nothing to do with the Traffic Department. They are rather the members of the National Guard, and their job is to protect the cell community from outside invasion. Like all real soldiers they always possess a brave nucleus. We also call them *phagocytes*, or 'cell eaters' (in Greek *phagos* stands for 'eating'), since they would attack and eat up most of the invading foreign cells. If you look around you will notice a few of them floating through the blood-stream and maintaining law and order. If they notice a bacterium, they will attack it right away, envelop it with their protoplasm and devour the invader in less than half an hour. If the invading bacteria are not in the blood-stream but somewhere in the lymph between the body cells, phagocytes force their way through the walls of the blood vessels and 'get their man' all the same. Their trouble is, however, that, in order to catch the bacterium, they must pin it against some solid wall, like the wall of the blood capillary for example; or else several of them have to attack the bacterium from different sides. If you look this way, you will see how it is done." Looking in the direction of Dr Streets's finger Mr Tompkins noticed several phagocytes who had cornered a bunch of bacteria and were getting ready to devour their prey. "If the bacterium floats in the middle of the blood plasma," continued the Doctor, "it is very difficult for a single phagocyte to grab it; about as difficult as it is for you to catch with your teeth an apple floating in a bucket. That is because most bacteria possess rather tough skins, the so-called capsules, which make them as slippery as the wet apple. However, the phagocytes are helped in their job by complex chemicals, known as *antibodies*, which appear in the blood during each bacterial invasion, 'softening up' bacterial skins as well as neutralizing the poisonous substances or toxins excreted by the bacteria into the blood-stream."

"I take it", said Mr Tompkins, "that these antibodies are not living creatures, since you refer to them as chemical."

"Quite right", agreed Dr Streets. "They are chemical—though rather complicated. The amusing thing about them is that they do not originally

exist in the organism, and are produced only when the organism is attacked for the first time by some bacteria or other. When such an attack occurs, the organism begins to produce antibodies specially suitable for the defence against that particular invader. They are, so to speak, tailored for each type of invader, and fit in like a key into a lock. It is likely that any living organism possesses, to start with, raw material for making the antibodies which can be quickly moulded into any suitable form. You might imagine, as an example, a locksmith's shop with a large collection of uncut keys. When the locksmith is called on to open a new and complicated lock, he would probably use a skeleton-key which can be adjusted and fitted into the lock by trial and error. This may be a lengthy process, but once it is done the locksmith can easily produce any number of keys answering the same purpose. And, if he is shrewd enough, he will keep a sample of that key in case he meets with an identical lock sometime in the future."

"Isn't that what doctors call *immunity* against the disease?" asked Mr Tompkins.

"Just so," was the answer, "and to form such an immunity as a preventive measure, we inject into a person a certain amount of dead bacteria, which, not being able to multiply, can cause no harm, but can still induce the organism to work out a suitable antibody to be used in case of actual invasion. This method.... Oh, wait a second!" And Dr Streets broke off, rising to his feet and trying to catch something floating through the plasma past their erythrocyte. "I think I can now diagnose your illness."

He was holding between his fingers a slippery object about the size of an apple.

"Is that a bacterium?" asked Mr Tompkins.

"Oh no! On our scale a bacterium would be as large as a dog. What you see here is a virus particle, and I would bet my professional pride that this is nothing else but the influenza virus."

"Oh, 'flu," drawled Mr Tompkins with relief; "so there is nothing to worry about!"

"Well, sometimes one can have a nasty case of 'flu. But I think you will be all right, and if you look here I will show you why."

With these words Dr Streets pulled at the object he held in his hands, and it easily separated into two parts. In his left hand was a round body with a rather rough-looking surface, and in his right a semicircular shell into which the other part was previously fitted.

"You see now," explained the Doctor, "this sphere here is the influenza virus, a single molecule built from many millions of individual atoms. You must have heard, of course, about the viruses, which lie halfway between living and non-living matter, and are sometimes called 'living molecules'. While bacteria can be considered as a kind of plant, secreting poisonous substances into the body of the organism they attack, viruses are the living poisons themselves. We may consider them as regular chemical molecules, since they always have a strictly defined atomic structure, but on the other hand we must also consider them as being alive, since they are able to multiply in unlimited quantities. Many diseases, such as influenza and poliomyelitis in humans, foot-and-mouth disease in cattle, and mosaic sickness in tobacco plants, are due to viruses, not to bacteria. And when you are attacked by a virus disease your organism learns how to produce the antibodies which can cope with that emergency. The empty shell which I hold in my right hand is the antibody for the influenza virus which covers it up and renders it inactive. Look how closely the surface details of the virus particle fit into the corresponding details on the inner surface of the antibody; this is the key-lock relationship I was talking about before. These antibodies float in large quantities through your blood-stream, catch the virus particles, clog them into clusters, and later eliminate them from your system. Since this particular virus particle, and a few others which I have noticed floating by, are already taken care of by the antibodies, I would expect that your 'flu will not develop into anything serious. I don't think you need even stay in bed."

"I think I like that key-and-lock analogy," said Mr Tompkins,

reflectively, "but I don't quite see who is the locksmith. Who makes them fit?"

"I don't see it too clearly myself," said Dr Streets, "and I doubt whether even my good friend, Linus Pauling of California Institute, who is an ardent advocate of the key-and-lock analogy, can tell you much more about it. The fitting is apparently done by the attractive forces between the atoms in the attacked invading particles, and those in the attacking skeleton-key antibody. I admit that it seems at first sight almost unbelievable that simple atomic forces can produce such remarkable structures, but you may begin to think differently if you remember the fantastic shapes of stalactites and stalagmites which are produced by nothing but water solution of calcium salts leaking through cave ceilings."

Dr Streets carefully fitted the influenza virus back into its antibody shell, so that it would not cause any more harm, and released it into the blood-stream.

"Aren't these antibodies going to attack me, since they must certainly consider me to be a foreign body in my own blood?" asked Mr Tompkins with some trepidation, "or would it be too silly to develop immunity against myself?"

"They certainly would if you stay here long enough", the doctor assured him. "But since you are, so to speak, a single particle, and don't multiply, it will take a long time to raise the alarm. However, it often happens that antibodies attack particles which are meant to be beneficial to the organism. That is why, in all blood transfusions, one should be very careful to select the proper type of donor."

"Oh, the blood groups", exclaimed Mr Tompkins. "I never thought that problem was connected with the disease-fighting agencies."

"It certainly is", retorted Dr Streets. "If, by some mistake, you had injected into your blood-stream the blood of a dog or a pig you would become seriously ill, since your antibodies would start a violent and devastating campaign against the alien erythrocytes. You might even die from thrombosis, as the doctors call it, if the debris of the battle clogged

the capillaries and prevented the circulation of blood. Now, within the same species the blood is largely interchangeable, but not quite. Human red blood cells may contain, among many other things, two particular proteins known as A and B. The blood plasma may contain, on the other hand the antibodies acting against these proteins; anti-A and anti-B we can call them. In some persons neither of these two antibodies is present, and they live happily with both A- and B-proteins in their blood cells. We call them A + B blood-type individuals. In other persons either anti-A or anti-B is absent (the other being present), so that erythrocytes may contain A or B proteins respectively. These are A and B blood types. Finally, it is possible that both antibodies are present in plasma, which leads to the O-blood type, deprived of both A and B proteins. In any individual human being the balance between the proteins and their antibodies is established from the early embryonic stage and there is no trouble. Again, if a blood transfusion takes place between two persons of the same blood type no harm will follow. But if the blood from an A-donor enters the system of a B recipient, the anti-A of the recipient's plasma will attack the erythrocytes of injected blood. This fight may often be fatal to the patient."

"I see now why they use plasma", exclaimed Mr Tompkins. "If the red blood cells are absent no fight can take place."

"You are nearly right, but not quite", corrected the doctor. "Even if the injected blood has no erythrocytes, it still contains in solution the antibodies which would attack the erythrocytes of the recipient blood, unless, of course, the donor is of A + B type. The point is, however, that mixing in a proper proportion the plasma obtained from persons of different blood types, one can prepare the so-called 'pooled plasma' in which the concentration of both antibodies, though not exactly zero, is sufficiently low not to cause any harm. But I am afraid I am getting too technical, and we'd better spend the rest of our time in surveying the other wonders of the blood-stream. I still have to show you some hormones and vitamins."

"Are they also living molecules?" inquired Mr Tompkins.

"Oh, no", said Dr Streets. "In many cases they are rather simple, and some of them can be synthesized from inorganic chemical compounds. *Hormones*, for example, whose name was derived from the Greek word *hormao* meaning 'to stir up' or 'to excite', are sometimes built from as few as a couple of dozen individual atoms. They are not the high executives of life, being more like orders or instructions sent out by these executives. They are just sheets of paper marked with ink carried around by couriers, but absolutely necessary for the smooth functioning of the business. If you take my lens and inspect the plasma floating past your palm you may be able to see some of these particles."

Following the doctor's advice and watching carefully the passing parade of the inhabitants of blood plasma, Mr Tompkins soon noticed a very interesting object. Under the lens it looked like one of the dragons seen in the streets of Chinatown during the New Year celebration. But it was less than one millimeter long, and (as Mr Tompkins rapidly counted), was formed of only twenty-two atoms.

"This is a molecule of *epinephrine* or 'scary hormone' which is produced by certain glands near the kidneys every time a person is frightened. Being rapidly carried by the blood-stream through the entire body, this hormone speeds up the action of the heart, causes the blood vessels to contract—thus increasing the blood pressure—and causes a release of sugars from the liver, providing the immediate source of extra energy for escaping the danger. The one which you have just seen is probably left over from the moment when you were scared by believing yourself on a sinking submarine. There are also many other hormones in all walks of life such as, for example, *secretin* which induces certain glands (pancreas) located just below your stomach to produce digestive juices at a higher rate, *testosterone* or male hormone which makes a man a man, and *theelin* which makes a woman a woman."

"But what about *vitamins*," asked Mr Tompkins, "are they in my blood-stream too?"

Fig. 3. Epinephrine, or "scary" hormone

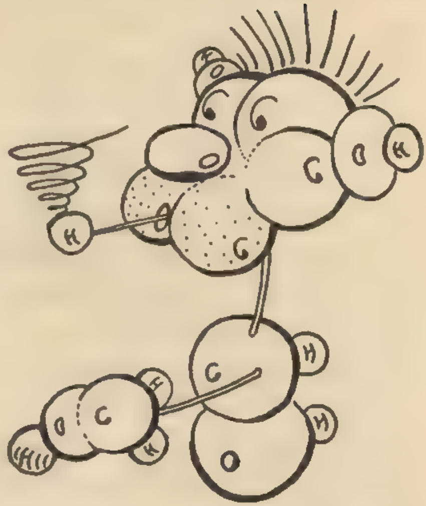


Fig. 4. Vitamin C, found in spinach

"I am pretty sure of that," replied Dr Streets, "since I believe your wife gives you the right sort of meals. Vitamins, as you probably know, are obtained from the proper foods and are absolutely necessary for health. A man needs over a dozen different vitamins, all of them comparatively simple substances which can be in many cases produced synthetically from inorganic material. You must certainly have heard about *vitamin C* which is present in spinach, green peppers, orange juice and tomato juice, and so on. Unless you get about sixty milligrams of that vitamin every day, you are liable to get *scurvy*: your gums begin to bleed and your teeth become loose. On the other hand the lack of *vitamin A*—found in butter, fat and fish-oils—causes a scaly condition of the eyes and night-blindness, whereas *vitamin D* (found in cod-liver oil) serves to prevent rickets, a disease involving malformation of the bones and unsatisfactory development of the teeth. But you can certainly find all the information about vitamins in any book on food and nutrition. You'd better look around now since we are entering one of the *villi* of your small intestine. Here is the

place where the blood absorbs the digested food you ate this morning, in order to carry it round to all the cells of your body. If you look through the thin transparent layer of cells separating us from the 'inside of your insides', you will notice a brownish mass of what was once bacon and eggs. It is now completely broken down by the digestive enzymes. The food you eat consists essentially of three chemical types: proteins, carbohydrates, and fats. The three types of enzymes, known as *trypsin*, *amylase*, and *lipase* attack respectively these three main food components, turning them into much simpler substances. Heavy protein molecules are broken up into much simpler amino-acids, carbohydrates are turned into sugars, and fats are split into glycerine and fatty acids. All of these substances are soluble in water and diffuse through the thin walls into the villi. Once inside, amino-acids and sugars get into the blood capillaries and are immediately dispatched into all parts of the body where they are expected by the hungry cells. The product of fat digestion is however much slower. Instead of choosing fast transportation through the circulatory system, they recombine again into tiny fat globules and move in a horse-and-van fashion through the lymphatic system. Lymph, as you may know, is a fluid very similar to blood plasma which fills the spaces between the tissue cells. It forms a waterway system as intricate as the channels in Florida's Everglades, where only the native Indians can find their way. And, like the Everglades' network of waterways, it is mostly stagnant water with very little or no current. So fat globules often form local congestions, causing fatty deposits in various parts of the body."

"Did you say," asked Mr Tompkins, who was hardly listening to Dr Streets's later remarks (which had got a bit dull anyway), "did you say that there is still some bacon and eggs left on the other side of the villi's walls? Since I've gone without my lunch I certainly shouldn't mind eating my breakfast all over again."

And, before the doctor could hold him back, he dived from their erythrocyte, and was already making his way through the thin layer of villi-cells separating him from the inside of his insides.

II. *They looked like giant tadpoles*

(*Courtesy of Dr Ralph Walter Graystone Wyckoff, National Institute of Health, Bethesda, Maryland*)

"Come back!" shouted Dr Streets in despair. "You will be eaten up by your own digestive enzymes."

"Too bad," he added, seeing that all his attempts were of no avail, "I should have told him about ulcers—when a man eats his own stomach."

* * * * *

Mr Tompkins was walking ankle-deep in a slushy substance which reminded him by its consistency and colour of an unsurfaced country road after heavy rain. These remnants of his breakfast did not look at all appetizing, and his hunger was completely gone. Suddenly he saw in front of him a large number of very strange animals playing happily in a muddy pool. They had big round bodies and short stocky tails, and reminded Mr Tompkins of some kind of giant tadpole. By wiggling their tails to and fro they were able to move their clumsy bodies at quite a considerable speed.

"I *don't* believe it!" said Mr Tompkins to himself; "I can't possibly have frogs living in my stomach, marshy as it is."

"They will never grow into frogs, they are phages", said a voice near him, and Mr Tompkins saw the tall thin figure of a man wearing patent-leather riding boots, a red and gold embroidered jacket, and a shiny black opera hat.

"I am Herr Max, the famous phage trainer", volunteered his new acquaintance. "Phages, as you may know, are a special type of virus, or mono-molecular organism, which feeds on bacteria. The particular breed of phages you see here attacks *Escherichia coli*, or simply *E. coli*—peaceful bacteria which help us to digest our food, and which can be found in quantity in everybody's intestines. I breed them here for my genetic experiments, and this particular strain is known as T_1. There are also six other strains, four of which have tails, and two which don't."

"Never knew molecules had tails!" said Mr Tompkins incredulously.

"And why not?" retorted Herr Max. "If molecules are big enough, and these here contain at least a million atoms each, they can afford a

luxury like a nice long tail. Of course, we can't yet write an exact structural formula of this particular chemical compound, but when such a formula comes to be written it will certainly show a long chain of carbons, oxygens, and hydrogens extending from the main body of the molecule. And the wiggling of the tail will be probably explained by the variable strength of the chemical bonds between atoms."

"But how do you know that these things are single chemical molecules?" insisted Mr Tompkins. "Why don't you also believe that real tadpoles, or even dogs for that matter, are single molecules too?"

"You can't crystallize dogs, can you?" said Herr Max with a smile.

"What do you mean, crystallize dogs?" asked Mr Tompkins sheepishly.

"I mean one can't form a crystal in which dogs (all of the same breed of course) would play the same role as water molecules in an ice crystal. This has been done however with some of the viruses, and I am sure it can be done with all of them, including these phages. Thus, for example, a virus attacking tomato plants and known as *tomato bushy stunt virus* crystallizes in the form of large and beautiful rhombic dodecahedrons. You could put such a crystal on the shelf in a mineralogical museum together with feldspar, and amethyst, and nobody would know that it is a colony of living organisms. And in a way it isn't, since, inside the crystal, the virus-molecule behaves just like any other chemical molecule. Now dissolve that crystal in a bucket of water, and spray it over a tomato plot. As soon as the virus particles find themselves within the cytoplasm of the plants' cells, they will begin to multiply rapidly. And, if you collect the sick plants, and separate the virus from their leaves you may get truck loads of the same beautiful rhombic dodecahedrons."

"Do they multiply by division, as cells do?" asked Mr Tompkins.

"No, they can't. They are single molecules, with each atom in its proper place, so they cannot either grow or multiply like ordinary living organisms formed of many molecules. When a virus particle gets into the substance of a cell in which it can live (and they are very choosy in

selecting their hosts) it uses the organic compounds of the cell to build exact replicas of itself. All viruses are fully grown the moment they are born, and all of them are exactly alike. When one of these phages here gets into a body of *E. coli*, and begins to multiply at the expense of its cytoplasm—that is, the substance of the cell as distinct from the nucleus—the bacterium is entirely eaten up in the course of thirteen minutes. Its skin breaks up, and a flock of about a hundred young phages comes out ready to attack other bacteria. Here, take a look."

With these words Herr Max led Mr Tompkins to what was once a beautiful *E. coli* bacterium. But there wasn't much left of it except its original shape, and its entire body was nothing but a wriggling mass of T_1 phages.

"Br-r-r-...how disgusting!" exclaimed Mr Tompkins, involuntarily raising his hand to his nose, "looks like a piece of meat that was left out of the icebox when the family went off for a summer holiday."

"Such is life", said Herr Max philosophically, using the butt of his long whip to push the phages about.

"Oh!" he exclaimed suddenly, with excitement. "If I am not mistaken, here is a case of a very interesting mutation. If I find any more mutants like it I can start few new *T*-strains."

And, forgetting about Mr Tompkins, Herr Max stepped into the wriggling mass of phages, inspecting each one with the greatest attention. Having no desire to follow him into the dissolved bacterium, and feeling a little sick, Mr Tompkins decided to try to find his way back into the blood-stream. He was, in a way, sorry that he had given up a comfortable ride on the erythrocyte for a slushy walk in his intestines.

Suddenly he felt a sharp pain in his leg and saw a giant leech biting his calf.

"Must be a trypsin or amylase", he thought, kicking it off with the other foot. "I really have got myself into a mess. There is no food left to speak of, and my digestive enzymes are getting wild with hunger. Better get out of here!"

But it was too late! The enzymes attacked him on all sides, and a couple of particularly bold lipases were already hanging tight on the fleshy part of his chin.

"Ouch!" exclaimed Mr Tompkins, and suddenly woke up.

A stout lady in the next chair in line turned her sympathetic eyes to him.

"Does it hurt much?" she asked. "I get bad pains too, and they make me scream. The doctor I went to see last week told me that unless I take care of myself...but you won't be interested in all the details. What's your trouble?"

"An attack by a flock of hungry trypsins, amylases, and lipases", said Mr Tompkins, who was just beginning to realize that he was back in the hospital waiting-room.

"That's a new disease to me," said the lady, "but I hope the doctor will help you."

But Mr Tompkins was already off his chair walking briskly towards the exit.

"There's no point in waiting for an ordinary doctor's diagnosis," he thought, "when the great Dr Streets himself has told me that I've got nothing more than a touch of 'flu. Besides, I mustn't be late at the bank."

Second Dream

GENE'S PIECE OF MIND

ONE evening Maud took their son, Wilfred, to the local movies to see the new full-length cartoon. This gave Mr Tompkins a chance to sit in his armchair and glance through a book on cell-structure and heredity which he had picked up in the local library. Although the language was very technical, and some of the passages did not make sense to him at all, he still felt that he was learning something.

It appeared that the heart of the cell, or rather its brain, was located in the darkish central body known as the *nucleus*. The nucleus seems to be a central agency which determines whether or not the colony of cells will take the shape of a frog or the shape of a man, and, in the latter case, whether the man will be tall or short, dark or blonde, a genius or a moron. The information concerning all these features is stored in long file cabinets known as "chromosomes", so-called simply because they could easily be coloured (*chroma* stands for colour in Greek) by certain organic dyes for microscopic work. Each cell within a given organism contains two sets of these file boxes, or chromosomes, one set coming from the father and one from the mother. Since the information, or orders, coming from paternal and maternal sets of chromosomes are not always the same, and sometimes even contradictory to each other, the result is usually some kind of a compromise. Thus a mule is closer to a horse in the size of its body, but closer to a donkey in the size of its ears (not to mention its stubbornness).

All this looked rather interesting, but not too persuasive, and putting down the book, Mr Tompkins reached for his whisky and soda. Taking a large sip, he looked lazily at the opposite wall and at the lithograph of the famous painting by Whistler hanging on it. Perhaps the drink he had mixed for himself was a bit too strong, but somehow or other the kind old lady in the picture seemed to become two, one of the images shifting slightly upwards and to the left. Mr Tompkins rubbed his eyes, took

another sip, and looked again. There were now three, no five, my-mothers, all of them sitting quietly with their hands folded on their laps. There was, in fact, a whole lot more of them, forming a continuous band winding and coiling in front of Mr Tompkins's eyes. Looking more attentively,

Fig. 5. There were three—no, five—my-mothers

Mr Tompkins noticed that none of the figures was an exact replica of any other; in fact it seemed that each of them stressed some particular feature of the original old lady, who now began to resemble Mr Tompkins's own mother, dead some years ago.

"Mother!" exclaimed Mr Tompkins, not quite believing his eyes.

"How are you, my son?" answered the entire display of old ladies in unison.

Now it began to dawn on Mr Tompkins that, through some strange interplay between the book he was reading, the state of his mind, and perhaps, some black magic, he was facing none other than one of the chromosomes which he had inherited from his dear old mother. The separate images along the chromosome must have been the genes or the individual centres of heredity about which he had read in the book.

"Mother—pardon me, Mothers," he said somewhat hesitantly, "are you my maternal chromosome?"

To his surprise, all the old ladies in the row, except the one sitting nearest to him, looked startled, as if they had never heard that word before. But the nearest old lady turned her head towards him, and said with a slight smile, "You are quite right my boy. What you see is one of twenty-four chromosomes carrying your maternal inheritance; and I am your *gnoceo-gene*, or the gene of knowledge.* Whereas your other gene-mothers take care of your various physical and mental characteristics, I am solely responsible for your interest in scientific problems."

"Haven't I also a gnoceo-gene from my father?" asked Mr Tompkins, remembering that the book spoke about complete sets of genes both from the maternal and the paternal side.

"Oh yes. But he won't be of much help to you in *this* respect. Your father, you see, was a very nice man and I loved him dearly, but he was a typical business man and was not interested in reading anything but the

* *Editor's note:* Later Mr Tompkins was unable to verify that such a gnoceo-gene actually exists, and that the "urge for knowledge" is not in fact the combined work of several different genes.

stock-market quotations. You can see him over there in your paternal chromosome which is lined up parallel to mine on the other side."

And in fact, Mr Tompkins noticed through a thick layer of chromatine a long line of men buried in their newspapers. Some of them had rather strongly marked features, but the one which was sitting in the place corresponding to that of his gnoceo-gene mother looked very inconspicuous indeed.

"I didn't know you were interested in science, mother", said Mr Tompkins, who remembered her always busy taking care of the house and the family.

"Not in my later years; but when I was young I used to read a lot on different subjects and even dreamt about a scientific career. But things turned out differently."

"How many gene-mothers and gene-fathers do I have?" asked Mr Tompkins looking at the long lines of his parents disappearing into the dim distance. "Seems to be quite a lot!"

"In this particular chromosome, which the scientists call *X*-chromosome, there are altogether seventeen hundred and fifty-three genes including myself. Of course, the geneticists do not know the exact number, and put it roughly at about two thousand, but living here as long as I have, I can count them all on my fingers. Come along, I will introduce you to some of them."

With these words gene-mother rose from her chair, and took Mr Tompkins by the hand.

"Here is your finger-print gene," she told him, leading Mr Tompkins along the line, "she takes care of the skin design on your fingers and toes."*

"How do you do, my son", said the old lady holding out her hand, and Mr Tompkins noticed that her finger-tips were soiled by some black substance.

* *Editor's note:* Mr Tompkins was unable to find the reference to "finger-print gene" in any of the books he looked up later.

III. *The long line of his parents disappearing into the dim distance ...*

(Courtesy of Dr Millslav Demerec, Carnegie Institution, Cold Spring Harbor, Long Island, N.Y.)

"Glad to meet you", said Mr Tompkins a little sheepishly.

"Here", continued his gnoceo-gene-mother pointing to a jolly looking old lady with a healthy ruddiness on her cheeks, "is your *antihaemophilia*-mother-gene who takes care that you do not bleed to death when you cut your finger accidentally. She is responsible for the production of substances known as *thromboplastin*, *prothrombin* and *fibrinogen* which are present in your blood and cooperate in coagulating the blood once it comes out from the wound. In some persons this particular gene is not in good health, and they are in constant fear of any minor cut. Since the genes travel from generation to generation, haemophilia is a hereditary disease, as are many other diseases caused by gene defects. But, as you can see yourself, you are safe from that danger. Be a good boy and shake the lady's hand."

"Glad to have met you", said Mr Tompkins following the invitation, and noticing that the gene's hand and forearm were all covered with small cuts and bruises.

"Oh, *that*," said antihaemophilia-gene following the direction of his glance; "you can't be too careful about these things, and I always keep inflicting little wounds on myself to be sure I am functioning all right."

"I would like to see", said Mr Tompkins jokingly, as they went further down the line, "the lady who is responsible for my moustache."

"Not in this chromosome!" retorted his gene-mother. "I have already told you this is an *X*- or female chromosome carrying only your maternal inheritance. To see the moustache and all that stuff you should go over to your *Y*- or male-chromosome. And I don't know that I should care to go with you.

"But here is your female sex-gene",* she continued, leading Mr Tompkins towards an attractive, but somewhat faded lady with a classical Greek profile. "You can't shake hands with her since she lost both of them to some barbarians who invaded the Island of Milos centuries ago."

* *Editor's note:* Here again it seems that both in *X*- and *Y*-chromosomes there are quite a number of individual sex-genes, determining the organism's different sex-properties.

"I don't see," said Mr Tompkins, "how a man can have a female gene."

"From the genetical point of view you are a half-a-man and half-a-woman," explained his gnoceo-gene-mother, "inasmuch as from your two sex-chromosomes only one carries the masculine properties, the other being entirely feminine. This is true of all human males, whereas all women are a hundred per cent pure, having two *X*-chromosomes. But your male-sex gene, over there in *Y*, is more aggressive, and produces *testosterone*, or male hormone, which completely suppresses the action of the feminine *theelin* produced by this nice lady. This is why you see her deprived of both her hands.

"But", she added with a twinkle in her eyes, "always remember that the two pinkish spots you have on your manly chest are there just in case you are going to have a baby."

"But what about all the other chromosomes I have?" asked Mr Tompkins. "Do they also show man and woman differences?"

"Oh no, the sex differences are limited only to one particular pair: the *X*- and *Y*-pair. The other twenty-three pairs carry other properties which are not linked with sex in any way.

"If you look at this picture from the family album", she continued, "you will easily pick up the sex-pair, since, unlike all other pairs, they differ from one another. The *X*-chromosome is about as long as all the others, whereas *Y*- is much shorter and somewhat crooked."

"You mean to say that there are more feminine qualities than masculine ones?"

"Not necessarily", said gnoceo-gene-mother. "The point is that the *X*-chromosome also carries a number of other properties, which have, in principle, nothing to do with the sex differentiation except that, of course, they are linked with sex by hereditary procedure. Your antihaemophilia-mother-gene—whom you met a while ago—is an asexual member of the *X*-chromosome. If she is not well, the inability of the blood to coagulate will be carried from generation to generation in accordance with the sex regulations.

"And here is still another example", she continued, leading Mr Tompkins towards a lady with tightly closed eyes. "This is your colour-vision gene, and as you see, she is unfortunately completely blind. This is why you were never able to distinguish between red and green."

"Why can't my father's gene help me in this respect?" asked Mr Tompkins with some annoyance, since his colour-blindness had occasionally put him to some inconvenience.

"As I told you, the colour-vision gene is essentially a feminine gene", explained his gnoceo-gene mother patiently. "All women have it in duplicate, one in each of their *X*-chromosomes, while the men have only one copy in the *X*-chromosome which they inherit from their mother. It so happened that one of my colour-vision genes was sick, which did not affect my colour-vision since it was taken care of by another duplicate gene. When, about nine months before you were born, my reproductive cells were breaking up, each into two parts, to form the so-called *gametes* (egg-cells in my case), half of the egg-cells got the defective *X*-chromosome. And it just so happened that your father's gamete, or sperm, met and married the defective egg-cell. It was a fifty-fifty chance that you would not be colour-blind, and I am sorry you had bad luck in this instance."

"I certainly had", retorted Mr Tompkins grumpily. "Neither you, nor father, nor Maud, nor our boy is colour-blind. What kind of heredity is it that affects only me!"

"A very normal one," said his gnoceo-gene-mother, "and you should have been able to work it out for yourself. You gave your little Wilfred a *Y*-chromosome, making him a boy and not a girl, and his *X*-chromosome is entirely healthy—coming from Maud. So he is quite all right. But if you ever have a daughter, with one *X* from you and one from Maud, the hereditary rules will begin to work. She will not be colour-blind herself, since Maud's gene will guarantee her colour-perception, but she will carry one defective gene, just as I did, and so her sons will have a fifty-fifty chance of being colour-blind, whereas half of her daughters will have one

defective colour-vision gene. Should she marry a colour-blind man, the chance of colour-blind female offspring will be fifty per cent. But you can certainly continue this arithmetic for yourself for as long as you like."

"But if women have two colour-vision genes, where the men have only one, colour-blindness must be much rarer among women", said Mr Tompkins reflectively.

"And so it is. In fact about one colour-vision gene out of ten is defective. Thus about one man out of ten is colour-blind, while in the case of women it is one out of a hundred. Very convenient, indeed, since a woman has to choose all her own dresses, whereas a man's colour problems are limited only to ties and socks!"

"But what about this new theory now accepted in Russia," asked Mr Tompkins, who remembered reading something about it in the newspapers, "doesn't it reject the regular gene-heredity, claiming that all the characteristics of the offspring are due entirely to environment?"

"You mean Lysenko's theory", replied his gnoceo-gene. "Western geneticists do not take it seriously, but, as a matter of fact, there are many cases in which Lysenko is undoubtedly right. Thus, for example, if Mrs P... gives birth to a baby who looks like her husband, Mr P..., we speak about gene-heredity. But, if Mrs P...'s baby looks more like Mr S..., a neighbour next door, the effect must be certainly ascribed to the environment."

"I see it all very clearly now," said Mr Tompkins, "but if, as you say, genes are always sitting tight in their chromosomes in the central nuclei of the cells, how can they control all the characteristics of the organism?"

"Oh, they do it through their close relatives known as *enzymes*", was the answer. "Each of the old ladies you have met in this *X*-chromosome has numerous daughters, all of them hard-working girls, who go out into the cytoplasm and direct chemical processes necessary for the wellbeing and development of their cell. If you follow me I will show you some of the enzymes at work."

With these words gnoceo-gene led Mr Tompkins out of the labyrinth

of chromosomes, and, passing through the thin nuclear wall they entered into the vast expanses of the cytoplasm.

"Here", said the gene-mother with a wide gesture, "are the fields where the main work of life is being done. The foodstuff which is broken up into comparatively simple organic material in your stomach and intestines is brought here by the blood-stream and hauled in through the cell walls. Then the enzymes begin their work of metabolism, designed to extract from the food the energy necessary for the maintenance of life. If I am not mistaken, here are some girls working on a molecule of sugar."

Approaching the group, Mr Tompkins saw twelve girls standing in a circle round a large sugar molecule.

"May I introduce Mr Tompkins, for whom we all work," said gene-mother with a smile. "And these are the members of the sugar-breaking team: Miss Hexokinase, Miss Oxoisomerase, Miss Phosphohexokinase, Miss Zymohexase, Miss Phosphotrioseisomerase, Miss Triosephosphatedehydrogenase, Miss...."

This introduction was, however, rudely interrupted by a large organic molecule which was rapidly approaching through the cytoplasm. All the girls turned their heads away from Mr Tompkins, and were watching the molecule with anxious faces.

"This is an ATP-molecule," explained gnoceo-gene, "a reverse of Parent and Teachers' Association. The full name is Adenosine-Triphosphate, and these glittering balls you notice on its front end are the phosphorus atoms of the three phosphate groups attached to the main adenosine body. The girls are going to use this ATP in the first step in the fermentation of sugar."

The first enzymo-girl, who was introduced as Miss Hexokinase, was now very busy manoeuvring the ATP-molecule into position much in the same way as a flight deck officer manoeuvres a Navy plane landing on a carrier. After several unsuccessful attempts, the ATP-molecule had finally assumed the correct position, with the outermost of its phosphate groups pointing directly at the central oxygen atom in the sugar structure.

Fig. 6. "Let it go!" shouted Hexokinase

"Let it go!" shouted Hexokinase, and with the powerful twist of a boxer delivering a hard left-hook Adenosine sent its three-phosphate arm into the body of the sugar. There was an audible impact, and the entire system seemed for a moment to be breaking up, but the bonds held, and the transferred phosphate group remained, still vibrating, in its new position.

"One down, and eleven to go," said gnoceo-mother, signalling to Hexokinase to come closer. "You can ask her to tell you more about the work of enzymes while the other girls finish the job. I am not too good on enzymology."

"It is very simple", said the girl, adjusting her spectacles. "All we have to do is to help various chemical reactions which would otherwise go too slowly. This big adenosine molecule would never get into a correct position if it were left merely to the law of chance. As you have seen, we enzymes do not do any physical work, but just *catalyze* the reactions by telling the molecules how to approach each other. In a sense we can be compared with missionaries who carry the 'word of gene' far and wide across the cell. Very often we work alone, but for more complicated jobs we join into groups which the scientists call *mitochondria*. This particular group here has the important job of getting the energy from the metabolism of sugar, and storing it in the phosphate groups of ATP. You may notice that Phosphohexokinase, my second neighbour on the right, is just getting ready to bring in another ATP-molecule."

"But", objected Mr Tompkins, "it seems to me that what you are actually doing here is getting the energy *from* ATP's instead of giving the energy *to* them."

"Oh, but this is only the beginning of the process, and we must indeed borrow some energy from the first two ATP-molecules to get things going. If you follow the entire show you will find, however, that at the later stages we give the energy back to the first two ATP's, and in addition produce three extra ATP-molecules by joining inorganic phosphates to the energy-poor adenosinediphosphates. Thus the energy liberated in the breaking-up of sugar molecules is accumulated in phosphate-bonds and can later be used at will for all kinds of purposes, ranging from putting the power into a boxer's punch to the rapid tail motion of a spermatozoon racing towards an ovum. It is also used for restoring the electric tension in the inner telegraph system of your nerves."

"You mean to say that my muscles work on phosphorus?" asked Mr Tompkins unbelievingly.

"Exactly. Your muscle-fibres are built of a complicated chemical substance known as *actino-myosin*, consisting of long molecules which normally coil up like a watch-spring. When ATP-molecules, produced in

the process you have just watched, come into the muscle tissue they use their energy to unwind these actinomyosin springs and to turn them into long straight ribbons. This is what one normally calls the relaxed state of a muscle. But as a matter of fact, the 'relaxed' state of the muscle is actually a very tense state, loaded with energy and ready to jump once a signal from the brain is brought in through a nerve. As Szentgyorgyi puts it, 'you work when you relax'."

"Is this Szentgyorgyi still another enzyme?" asked Mr Tompkins, a little stupefied.

"Oh no, it is just a Hungarian's name. But he catalyzed oodles and oodles of biochemical work, and also discovered paprika."*

"Would you like to walk around and see the other enzymes working in your cell? There are a lot of other things they do", his gnoceo-gene said.

"I would like to," said Mr Tompkins, "but there is one thing that I would like to see most. Can you show me the process of cell-division?"

"You are rather old for that", retorted his gene-mother, "and in your body the cells do not undergo mitosis very often. If you want to see the process of cell-division, I recommend that you visit the part of your body which is hiding under the shadow of the fig-leaf. This is about the only place where your cells multiply at full speed, as long at least, as you can still father a child. And when you get there ask for some good biophysicist, Doctor Netherlander for example, who can give you all the necessary explanations. Good-bye, my son, and good luck!"

* * * * *

Arriving at his destination Mr Tompkins found that the place was really full of activity, and that the cell-division processes, which he wanted so much to see, were taking place all around him. In fact, it was hard to find a cell which would not break in two before one can pronounce *spermato-*

* *Editor's note:* Must be a slip of the tongue on the part of Hexokinase. Dr A. Szent Gyorgyi separated vitamin C *from* paprika (and also got the Nobel Prize for it).

genesis. A bespectacled middle-aged man with a note-book in his hand was busy taking notes on individual division processes.

"Excuse me, please," said Mr Tompkins, "but can you tell me where I can find Dr Netherlander?"

"I am Dr Netherlander," said the man; "and whom have I the honour of addressing?"

"My name is Tompkins, originally from Wonderland. You may have read about my adventures in relativity and quanta."

"Oh yes, of course," said Dr Netherlander, "I think I have heard your name before. So now you are going to invade biology?"

"I've seen many interesting things already in all parts of my body, but this is the first time I've seen cell-division. Looks very exciting."

"You've noticed, of course, that what is happening here is mostly *meiosis* and not *mitosis*", said Dr Netherlander, putting the note-book into his pocket.

"What's the difference?" asked Mr Tompkins with slight embarrassment.

"I see you need a short lecture", said Dr Netherlander with a touch of boredom in his voice. "*Mitosis*, or regular cell-division, takes place in all the tissues of growing organisms. You know of course that each of your body-cells contains twenty-four pairs of chromosomes, one set from your father and one set from your mother?"

"Yes, my mother gene told me so", put in Mr Tompkins.

"Mother gene or mother goose does not matter, but that's how it is. When such a cell is going to divide, each of the forty-eight chromosomes splits in two along the axis, and the two halves are pushed apart into opposite corners of the cell which then also breaks in two. This guarantees that the two daughter cells have exactly the same constitution as the cell from which they are formed. In fact, any cell in your body possesses a complete set of information about all your physical characteristics. Experiments were made in which a piece of skin from the belly of a frog embryo was placed on the face of an embryo of a salamander, and vice

versa. As a result the frog developed the facial features of a salamander and the salamander's face looked like that of a frog. This proves that cells from any part of the body know exactly how other parts of the body should look and will use that knowledge if called upon to carry out the task.

"On the other hand, *meiosis*, or reductive division takes place only in the reproductive organs, and leads to the formation of male sperms and female eggs. In this process chromosomes do not split at all, so that each of the two daughter cells gets only one set of chromosomes. This is what is taking place here. Watch this cell, for example."

And Dr Netherlander pointed to a large cell tightly squeezed between the others, right in front of them.

"You notice", continued the doctor, "that, in preparation for the division, the nuclear wall is already dissolved, and all the chromosomes have lined up along the central plane of the cell. In a minute you will see one half of the chromosomes moving upwards, and the other half downwards. Here they go!"

And, indeed, the chromosomes started to separate as if pushed by two invisible hands and a few minutes later* took up their positions at the opposite ends of the cell.

"Looks like a hippo opening his mouth", said Mr Tompkins, watching the unusual spectacle. "But what are those long darkish bands which remind me of the hippo's lip-corners?"

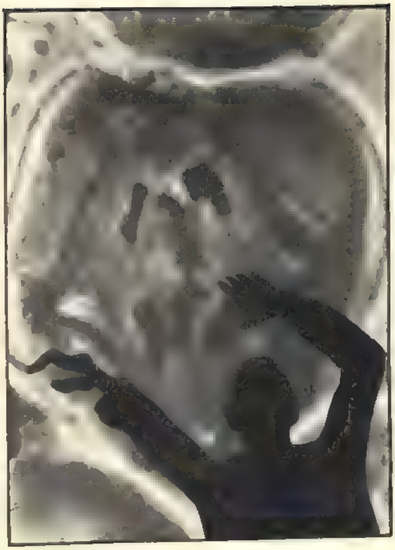
"Oh, those are *mitochondria* which contain most of the cell's enzymes, and are also the carriers of cytoplasmic heredity."

"You mean to say that hereditary properties are not necessarily carried by chromosomes?" asked Mr Tompkins in surprise.

"Most of them are, but undoubtedly there are also some properties which are carried by the cytoplasm of the cell. The problem is quite complicated and the relative roles of the nucleus and the cytoplasm in the life of the cell are not yet completely cleared up. But look, now! While we were

* *Editor's note:* The distortion of the time-scale again. In a human being the reproductive division process occupies altogether 80 minutes.

. . . he chromosomes are lined along the central plane . . .



. . . as if pushed by two invisible hands . . .

. . . looks like a hippo opening his mouth . . .

The wall is now growing along the central plane

IV. *Before one could say "spermatogenesis" . . .*

talking, the two separated chromosome groups have coiled up again into two nuclei, and a wall is now growing along the central plane to complete the division. Thus instead of one *diploid* cell with two sets of chromosomes, you now have two *haploid* cells with only one set each. Later they will grow tails and become two regular spermatozoa destined to carry on the noble name of Tompkins. The one which got a *Y*-chromosome in the reductive division would give you another boy, whereas the other with *X*-chromosomes will beget a girl."

"But why should my spermatozoa carry only one half of my properties?"

"Because", said Dr Netherlander, "the other half is supplied by the egg-cell of your wife. These egg-cells also originate by the splitting, or meiosis, of the regular diploid cells forming the body of a woman. Of course, all of them are identical, and carry one *X*-chromosome. When male sperm and female egg meet, they fuse together into one diploid cell which begins to multiply in a regular way, growing into a boy if the sperm who won the race had a *Y*-chromosome, and into a girl if it was another *X*-chromosome."

"Quite complicated, I declare", said Mr Tompkins. "So, I presume a sex-life is the privilege of only those complex organisms which can make all these arrangements?"

"Not necessarily", was the answer. "In fact, a friend of mine, a Hungarian who has recently forged his Geiger counters into a microscope, insists that bacteria have a sex-life of their own although they do not indulge in it too often. But when they do, two bacteria come together, exchange their chromosomes and genes and then part again as total strangers. Even viruses and phages seem to follow this practice. In fact, if there were no exchange of properties between individual organisms, the evolution of the organic world would be considerably slowed down."

"I have read somewhere", said Mr Tompkins, "that evolution results from things they call mutations."

"That is true. And indeed, without mutations the exchange of genes

and chromosomes would not bring us anywhere. You can re-mix the genes of an ape, or whatever our ancestors were, as much as you like, and you never get *homo sapiens*. You can't make a martini from a manhattan by just re-mixing its components.

"Mutations are the spontaneous changes taking place within individual genes. As you know, each gene is a well-defined molecule, whose structure determines completely the particular characteristics of the organism for which it is responsible. But the molecules, like anything else, are not necessarily permanent, and can undergo internal structural changes in which one or other atomic group is transplanted to a different position. If this happens the mutated gene will give somewhat different orders to its subordinate enzymes in the surrounding cytoplasm, and the entire cell will start to behave in a new way. Of course, the mutations which take place in the various cells of your body are unable to change any of your own properties, since you represent a colony of some thousand million millions of cells, and the fact that a few of them alter their behaviour cannot influence the entire system. But if a mutation takes place in one of your reproductive cells, it will result in identical changes in every single cell of your child and can lead to noticeable macroscopic differences in its physical and mental properties. There are virtually millions upon millions of possible mutations, most of them irrational and harmful, while a few of them may be very beneficial to the organism. Nature brings in the mutations in a blind and random way, and it is up to *natural selection* to eliminate the unsuccessful mutants and to carry on the evolutionary process along the lines of the successful ones."

"Yes, I know that", said Mr Tompkins, who was a student of Darwin. "But tell me more about the causes of these mutations."

"Well, for one thing," said Dr Netherlander, "there are so-called natural mutations caused by the thermal motion of gene molecules. As you know, heat is a statistical phenomenon, so that thermal vibrations of various parts of a molecule, being of about the same intensity for any given temperature, may accidentally become more violent than the average.

If one of the atomic groups constituting gene-molecules were to become involved in such an abnormally strong motion, it might get detached from its customary place, and, sliding along the gene, anchor in some other spot. The mutated gene will now be giving different orders to the cell, which may lead to a change in the colour of the eyes, the growth of a sixth finger, increased power of reasoning, an inclination to dyspepsia, the development of artistic taste, or any other of the millions of possible changes."

"Does that mean that people living in a hot climate mutate more often than those in a cold climate?" asked Mr Tompkins with interest.

"Not in the case of people, since we are warm-blooded animals, and the body of an African negro is maintained at about the same temperature as that of a Lapland eskimo. But cold-blooded animals such as flies, definitely show that effect. Thus, fruit-flies, known as *Drosophila melanogaster*, undergo one common mutation which makes their usually dark red eyes turn bright vermilion. If you breed these flies in enclosures at different temperatures, you will notice that the usually small percentage of baby flies with vermilion eyes increases quite considerably with the temperature. In fact, this increase of mutation-rate follows the same simple rules as the increase in the rate of ordinary chemical reactions carried out at various temperatures.

"Then, of course, there are also mutations produced by various kinds of ionizing radiations such as ultra-violet, X-rays, and the high-energy radiation emitted by radioactive materials. If a fast electron produced in living tissue by these radiations hits some part of a gene, that part can be kicked out of its customary place and attached to a different location. If we knew the detailed structure of genes, and if we could aim electrons as we aim rifle bullets we could produce at will any desired changes in living beings. But, of course, it is quite impossible, and, just as in the case of thermal mutations, changes produced by radiation take place quite at random. It seems, in fact, that some natural mutations are due to the effect of the so-called cosmic rays—a very diluted stream of high-energy radiation falling on our earth from the interstellar space."

"But what about the radiation of the atomic bomb and its fission products?" asked Mr Tompkins who had been painfully conscious of that subject ever since the Hiroshima announcement.

"In very mild doses", said Dr Netherlander, "these atomic radiations will produce the same effect as weak X-rays in causing gene mutations. But, of course, in the case of high-intensity radiation, a large proportion of cells in the organism will be badly affected, resulting in the so-called radiation sickness and eventual death. In that case it is not helpful to talk about the mutations of individual genes, just as it would be pointless to discuss thermal mutations in the body of a lobster being cooked in boiling water. In fact, strong radiation doses seem to be more effective in destroying the cytoplasm of the cell than the nucleus and its chromosomes, but we do not know exactly why."

"How much radiation is necessary to kill a man?" asked Mr Tompkins, who did not quite understand these last words.

"For a sober man a lethal dose of radiation is about four hundred of the units known to radiologists as Roentgens."

"What do you mean: for a *sober* man?" asked Mr Tompkins with great surprise.

"Well, you see," smiled Dr Netherlander, "I have recently discovered an antidote which almost doubles the resistance to radiation." And he extracted from his pocket a bottle of fine Scotch whisky. "Take it all a few minutes before being exposed to radiation," he said, handing it to Mr Tompkins, "and your chances of survival in an atomic attack will be considerably increased. But will you please excuse me? I have to return to my experiments."

Left alone, Mr Tompkins decided to watch a few more division processes. But suddenly he was distracted by a noise as of thunder coming from above his head. He looked up, and there high in space was a cluster of small yellow balls rushing wildly towards him.

"A cosmic ray shower!" flashed a thought in his brain. "And it is coming right at me!

"But surely it's all right", he tried to reassure himself. "After all, what can a few atomic particles do to a man?

"But I am not a man!" flashed another thought. "I am no larger than a gene!"

The shower of particles was now quite close, and one of them, emitting an ominous yellow glow, was heading right toward Mr Tompkins. Stricken with fright, he quickly raised the bottle given to him by Dr Netherlander and drank it straight off.

Bursting fireballs and bright luminous arches began to jump in front of his eyes. Cells, chromosomes, and mitochondria began to rotate faster and faster around him, and for a second he lost consciousness....

* * * * *

When he opened his eyes again he was sitting deep in his armchair. He was glad to see the familiar outlines of the drawing room; and the Whistler painting was hanging, as usual, on the opposite wall.

In his hands was an empty whisky bottle. He shoved it hastily under the chair as he heard the voices of Maud and Wilfred returning from the movies.

Third Dream

BRAINY STUFF

When Mr Tompkins arrived at the bank in the morning he found the entire staff in a state of great excitement. Both the manager and the assistant manager were away from their desks, and several tellers' windows were closed, with long lines of customers loudly complaining in front of them.

"What's the matter?" he asked another clerk who had just run upstairs from the basement.

"Don't you know?" replied the clerk excitedly. "We've just got a new punch-card machine. Go down and look at it."

It was cool and quiet in the spacious basement of the bank building. A crowd of employees stood in a semicircle round a large metal cabinet, watching a kneeling man in grey overalls who was adjusting some electric contacts.

"Well, we have seen all that is to be seen," said the manager, "and now, back to work!"

Everybody rushed back to the main floor except Mr Tompkins, who could not take his eyes from the machine.

"Interesting?" said the man in grey overalls, rising to his feet.

"Very", replied Mr Tompkins. "I always wanted to see a machine which, as they say, could serve as a substitute for the human brain."

"Well, this one doesn't do much in that line, and can't be compared to much more than the brain of an average business man", said the man in grey overalls, slapping the metal wall of the cabinet patronizingly. "But, if you want to see the real McCoy, drop in some time after work to our Electronic Brain Laboratory, and meet The Maniac."

"I certainly will", said Mr Tompkins, with enthusiasm.

* * * * *

When, later that day Mr Tompkins passed through the broad doorway of the Electronic Brain Laboratory, he was met by a good-looking young man with a small dark moustache.

"Mr Tompkins, I presume", said the young man, smiling and holding out his hand. "One of my technicians told me you meant to drop in. I am the chief mathematician here and I shall be glad to introduce you to my brainchild, The Maniac."

And he directed Mr Tompkins to a large machine standing in the middle of the room. It consisted of a multitude of monotonously repeated vacuum tubes, and wire connexions, and at first glance it looked like an enormously extended version of the automatic telephone exchange in the bank.

"Here it is, the king of all acs.", continued the young man proudly. "It contains about three thousand vacuum tubes including forty specially big ones used for the memory. It can add two numbers, with twelve decimal places each, in about two hundred-thousandths of a second, and can multiply or divide the same two numbers in less than one thousandth of a second. And it can keep in its memory no less than one thousand and twenty-four numbers, recalling them whenever needed for computation. We have here a problem about the inner structure of stars, a problem which, according to our estimates, would need the work of one hundred girl computers for one hundred years. Well, The Maniac will do it in a few days."

The mathematician threw several switches and The Maniac came to life. Its three thousand tubes began to glow, as if it were waiting, eagerly.

"Write a problem, any problem", said the mathematician pointing at the paper tape which was being fed into the machine from a large roll.

Mr Tompkins was not very good at higher mathematics, but he certainly knew his multiplication tables. With a bold hand he wrote:

$$21 \times 7 = \quad .$$

As his writing disappeared into the receiving slit of the machine, he

could hear a strange hissing which quickly turned into a loud shrill noise. Bright sparks began to jump inside the machine, several big memory tubes burst with a loud clap, and The Maniac stopped dead.

"Was my problem too tough for him?" asked Mr Tompkins with a touch of pride.

"No, it was my mistake", said the mathematician inspecting the injured part of the machine. "I forgot to tell you that the problem should be written in the binary system, which uses the power of two."*

"Sounds like Greek to me", confessed Mr Tompkins.

"I see you are not much of a linguist", the mathematician smiled. "What I said was in pure English; in Greek it would sound as: Τὸ πρόβλημα πρέπει νὰ γράφεται μὲ σύστημα δυάδων, μεταχειριζόμενοι ὡς βάσιν δυνάμεις τοῦ δύο."

"I still do not see the point", protested Mr Tompkins.

"Very well", said the mathematician patiently. "I will try to explain it to you in simple words. The Maniac, like most of the other acs., can only count up to two." ("Oh", drawled Mr Tompkins disdainfully.) "The fact that we humans use the decimal system, counting in powers of ten, resulted simply from the anatomical peculiarity of having ten fingers on our hands. We write 1, 2, 3, ... 9 as we fold our fingers one by one, but when all our fingers are folded we write 10 meaning: one 'full-hands' and no extra fingers. Then comes 11, i.e. full-hands and one, 12, full-hands and two, etc. The full-hands of full-hands is written as 100, and full-hands of full-hands of full-hands as 1000. Sometimes people count in dozens, and we write it down in a way similar to the decimal system if special single signs are adopted for ten and eleven. In such a dodecal system '13' will mean: one dozen and three, i.e. fifteen, and '125' is a dozen dozens, plus two dozens plus five, i.e. 173. A binary system could be developed by persons who, instead of counting on their fingers, count on their arms. Such a person would write 0 if no arms are counted, and 1 if there is only one

* *Editor's note:* Since this accident The Maniac has been equipped with a special auxiliary device which translates the figures from the decimal into the binary system.

arm. Two arms will be counted as full-arms (since the person has only two arms), and will be represented as '10', i.e. *one* set of full-arms and *no* extra arms. In your example the first factor (21) can be written as

$$1\cdot2\cdot2\cdot2\cdot2 + 0\cdot2\cdot2\cdot2 + 1\cdot2\cdot2 + 0\cdot2 + 1 \text{ or } `10101\text{'}.$$

The second factor (7) is $1\cdot2\cdot2 + 1\cdot2 + 1$ or '111'. One can easily learn to multiply that way and the multiplication tables one would have to memorize would consist of only four lines:

$$0 \times 0 = 0,$$
$$1 \times 0 = 0,$$
$$0 \times 1 = 0,$$
$$1 \times 1 = 1,$$

thus making all school-children happy. Let me carry that multiplication for you."

And, taking a piece of chalk, the mathematician wrote on the blackboard:

$$\begin{array}{r} 10101 \times 111 \\ 10101 \\ 10101 \\ 10101 \\ \hline 10010011 \end{array}$$

"Are you sure it's right?" asked Mr Tompkins, "it looks such a long number."

"Check it yourself", said the young mathematician. "The first unit on the left stands for the seventh power of two, that is, 128. Then you have the fourth power of two, or 16, the first power, that is, two itself, and finally one unit. Add it up and you get 147 which you also obtain by multiplying 21 by 7 in the ordinary decimal system."

"But why do you have to build your machinery on the binary system instead of the decimal, which is used by everybody else?" inquired Mr Tompkins.

"It's much simpler that way," said the mathematician, "and, in fact, Mother Nature uses exactly the same system in the complicated machine which you call your brain. Both the *neurons*, or nervous cells which form your brain, and the vacuum tubes of electronic computers are capable of only two states: excited and non-excited. In speech it would be the equivalent of 'yes' or 'no', and in the binary counting system to '1' or '0'. Of course, one could design more complicated vacuum tubes which would have ten different responses, but why bother? It is much simpler to turn decimal figures, based entirely on the anatomy of man, into the more natural binary figures. Of course, numbers written entirely in ones and zeros look longer than their decimal equivalents, but it only means that we have to build more columns of tubes in the computer. Maniac can handle numbers up to forty binary places, which is equivalent to twelve decimal places. But, speaking about tubes, will you please excuse me for a few minutes. I must go into the storage room and get substitutes for the tubes which The Maniac burst in his attempt to handle decimal figures."

Left alone, Mr Tompkins sat down on a large cardboard box marked "Fragile: Glass" (there was no other comfortable seat in the room), and looked again at The Maniac. It seemed to him now that the machine was much more human than he originally thought, and he was not at all surprised when The Maniac winked at him with his left eye.

"Smart, isn't he?" said The Maniac in a resonant metallic voice. "And he is sure that he is my master, while, as a matter of fact, he is simply my servant."

"Nobody told me that you could speak as well!" exclaimed Mr Tompkins with great surprise.

"Oh, they don't know a lot of things about me. They think I'm some kind of robot-slave. But, even though I have only three thousand tubes, I can beat, in many respects, the smartest human with several thousand million neurons inside his skull. I am now learning to play chess, and when I am through, I am going to checkmate the chess champion of the world. That is how good I am!"

V. *The Maniac spoke in a resonant metallic voice*

(Courtesy of Mr Charles Lehman Los Alamos, New Mexico)

"Then will you be so kind as to explain to me in more detail how you function, and what are the deeper relations between you and the human brain?" asked Mr Tompkins with interest. "Or isn't there enough time for that?"

"Oh, there's plenty of time", said The Maniac. "There is usually quite a mess in the storage room, and my attendant will probably spend a lot of time trying to find the proper tubes."

"But, how is it that you are able to function when some of your tubes are burst?" wondered Mr Tompkins.

"Oh, that's nothing", said The Maniac. "You probably don't know that the famous French scientist, Louis Pasteur, had, fairly early in his career, a severe haemorrhage in the right hemisphere of his brain. This left him, for the rest of his life, partially paralyzed on one side of his body, and years later—after he had died—the autopsy showed that the damage was indeed so serious that he must actually have lived with one half of his brain only. Yet this damage did not affect his mental ability in the least, nor could it prevent him from doing some of his best work.

"Of course, if it had been the left hemisphere, or if Pasteur had been a left-handed person things would have been much worse."

"What has it to do with right- or left-handedness?" asked Mr Tompkins with surprise. "I always thought that was a very minor detail."

"Oh no, actually it is much more important than one usually thinks", replied The Maniac. "The point is, that although both sides of the human brain are equally adapted to higher mental activity, it is actually only one side which takes a leading part. While in the intellect of the lower animals, such as cats or mice, both sides of the brain divide their mental functions about equally, in man the functions are usually concentrated on one side while the other remains more or less dormant. If the left hemisphere becomes the dominant one, the person becomes right-handed, since, as is well known, the nerves leading from the brain to the body cross over on their way down. If, on the other hand, the dominant hemisphere is the one on the right, we will have, naturally, a left-handed person. This

explains, for example, why left-handed children who are forcibly taught in school to use their right hand often become stutterers and develop defects of speech, reading and writing. The forcible use of the right hand by naturally left-handed persons leads to the development of dormant centres in their left hemisphere, which may interfere with the activity of primary centres in the right hemisphere. And when the orders come from two different places a mix-up can easily result."

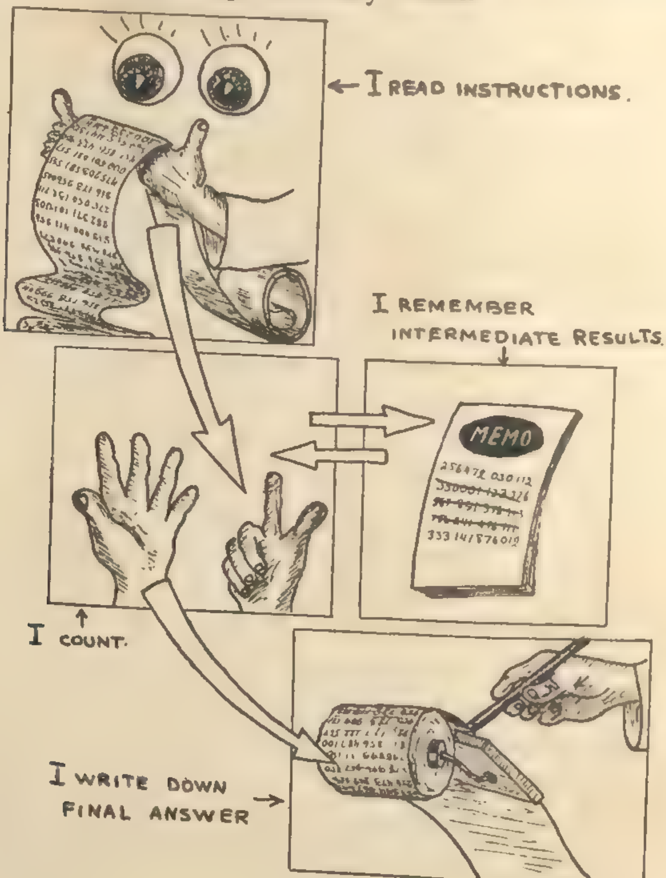


Fig. 7.

(For simplicity numbers in Fig. 7 are given in the decimal and not in the binary system.)

"Isn't it similar to the conflicting orders which may be given by paternal and maternal chromosomes in the progeny's cells?" asked Mr Tompkins.

"Never heard of any such things", grumbled The Maniac, and Mr Tompkins realized that, in spite of his phenomenal ability in one very narrow field, the robot was quite ignorant on most other subjects.

"But", said Mr Tompkins trying to bring the conversation back to a subject familiar to The Maniac, "I still don't quite see how you reason and solve complicated mathematical problems. Would you mind telling me in more detail?"

"Certainly," said The Maniac with an air of decided superiority, "but you must promise not to mind if I talk down to you."

"I promise", said Mr Tompkins.

"You see," started The Maniac, assuming the air of an experienced lecturer, "when I am given a problem I first read and memorize the instructions how to handle it. These instructions must be written, of course, in machine language; coded as they call it. I make the computations, keeping in my memory the intermediate results, and when I come to the final answer to the problem I write it out and stop.

"Here, for example," he continued pulling from a waste-paper basket a piece of paper tape with long rows of holes punched in it, "is a problem they gave me yesterday to demonstrate my abilities to some important visitors. I was asked to solve a quadratic equation:

$$15x^2 + 137x = 4372,$$

or, in the binary system:

$$1111x^2 + 10001001x = 1000100001100.$$

Of course, as you probably remember from your school days, there is a special formula for the solution of that simple equation. I have that formula, along with lots of other formulae and tables, permanently recorded in a special attachment to my memory; my information library, so to speak.

"In this case, however, they wanted me to do the job the hard way by trying the values for *x* of one, two, three, and so on until the correct value is found. And, as you see, the instructions for doing it run roughly as follows:

(*a*) Remember the number 1111.
(*b*) Remember the number 10001001.
(*c*) Remember the number 1000100001100.
(*d*) Remember the number 1.
(*e*) Multiply the fourth number by itself.
(*f*) Multiply the result by the first number.
(*g*) Remember what you got.
(*h*) Multiply the fourth number by the second.
(*i*) Add it to the previous result.
(*j*) Compare that with the third number.
(*k*) If the result is smaller than the third number, take the fourth number and add *one* to it.
(*l*) Forget (or erase) the old fourth number and remember the new one instead.
(*m*) Proceed as before using the new value of the fourth number.
(*n*) When the result becomes larger than the third number, memorize it and look for the next instruction.
(*o*) Put *one* in the next digital place of the fourth number.
(*p*) Multiply, etc., etc., etc.

"Well, the instructions were perfectly clear so I got on with the long task. I multiplied one by one, getting one, and multiplying it by the first number got 1111. Making a note of that in my memory, I multiplied 10001001 by one, getting 10001001. Adding it to the previous result, I got 10011000 which was clearly smaller than the third number, which I remembered to be 1000100001100. So, following the instructions, I added one to the fourth number (which was also one) and got two. Using two instead of one, and multiplying it first by itself and then by 1111, I got 111100.... Well, I won't bother you with all the details of my

calculations, and will only say that when the fourth number was 1101 (or thirteen in your human language) the result was still smaller than the third number which I still kept in my memory. But when I took x 1110 (or fourteen) the result was too large. The solution of the equation was clearly between thirteen and fourteen."

"Couldn't you give it more exactly?" inquired Mr Tompkins.

"Of course I did. Having obtained this first result, and having followed further instructions I started trying out the numbers 13·1, 13·2 and so on until 13·9. And when I found that the correct answer lies between 13·1 and 13·2, I tried for x the values from 3·11 to 13·19. And in the end I came out with the correct solution, with forty binary, or twelve decimal places."

"How long did it take you to do all this work?" inquired Mr Tompkins with professional interest.

"Well, let's see. I had to do altogether about five hundred multiplications, and some additions which, of course, go much faster. One millisecond per multiplication would make it altogether just about half a second to get the final answer. And, mind you, I should have done it just as fast if all the coefficients in the equation had had twelve decimal places. In fact, it takes me just as much time to multiply 2 by 2 as to multiply 275036289706 by 573024696271, since in any case I always have to go through the entire register to be sure there is no other figure placed in it. Simple problems do not pay when you deal with electronic computers, because it takes much more time for my attendants to code them than for me to solve them."

"So, your brain processes really go much faster than in the human brain", said Mr Tompkins with respect.

"Oh, yes. About a thousand times faster. A synapsis by a neuron takes about one millisecond, while a reaction by my electronic tube is completed in only about one microsecond. Then, of course, I am much better trained than human beings in handling numbers—at the expense of such useless activities as remembering poetry or composing music."

Mr Tompkins was quite thrilled by being able to understand this complicated piece of electronic machinery, but his thoughts kept returning to the functioning of the actual human brain.

"You have mentioned", he said, "that speech abilities are localized in certain definite parts of the brain. Does that also hold for all other aptitudes?"

"Certainly", was the answer. "In fact, all the sensory and locomotive centres concerned with the different parts of your body have fairly well-defined positions on the surface of your cerebrum. You can see it best by looking into the brain mirror hanging over there in the corner. It amplifies all the principal features of your brain, but reduces all the other

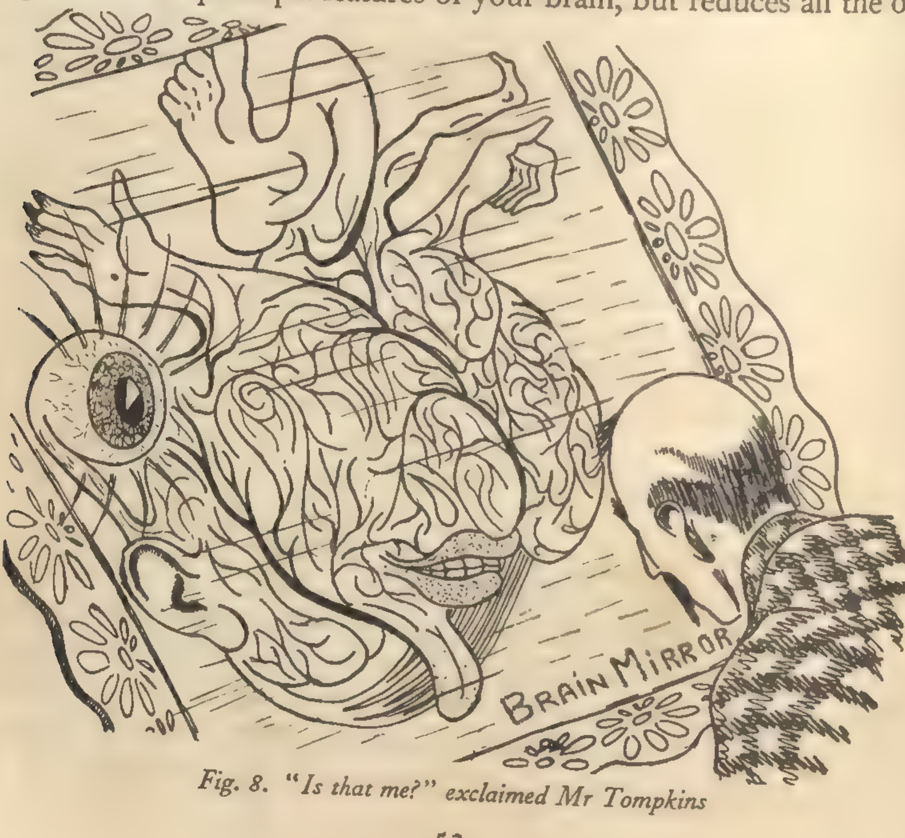


Fig. 8. "Is that me?" exclaimed Mr Tompkins

parts of the body, turning them into small appendices attached to the surface of the brain where the corresponding nervous centres are."

Mr Tompkins walked over to the mirror, but after one glance backed away in horror; the creature which looked at him from behind the glass defied all human imagination. It resembled a large sack of some grey material with its surface folded up in numerous fissures. Attached to this shapeless body were short stocky arms and legs, a large pair of lips with a tongue hanging below them, and a pair of eyes protruding from behind the ears. The whole thing looked like the well-known picture of a Martian in an illustration of H. G. Wells's fantastic novel *The War Between Worlds*.

"Is that me?" exclaimed Mr Tompkins in disgust.

"Certainly it's you", said The Maniac. "And, in fact, this mirror amplifying your brain features does not make you look much worse than some curved mirrors you can find in amusement parks. Or at least it does you more justice."

Going back to the mirror, Mr Tompkins could now recognize the basic features of the brain, which he had seen before in anatomy books. There was a deep central fissure separating the brain into a right and left hemisphere, and another fissure running upwards and towards the back along each hemisphere separating the brain into the frontal and occipital lobes.

"You will notice", said The Maniac, "that your legs, arms, mouth and tongue are attached to the frontal lobe of your brain, since, in fact, that is where most of the motor centres governing your motions are located. Sensory centres, like eyes and ears on the other hand, are located at the back of your head."

"Isn't my tongue also a sensory organ?" protested Mr Tompkins.

"Well, nobody knows exactly where the taste centres are, and they might just as well be in the back lobe. But the main motor function of the tongue is the moving of food, and of course speech; this is certainly located in the frontal lobe. You may also notice that your lips and tongue are located essentially in the left hemisphere, showing that you are a normal right-handed person."

"It would be so nice to get in there and do a bit more exploring", Mr Tompkins said dreamily; for, ever since his journey through the blood-stream, he had regretted that hunger had prevented him from visiting his brain.

"Why don't you go in there?" said The Maniac.

"You mean through the glass?" asked Mr Tompkins in surprise.

"And why not? Haven't you ever heard of Alice?"

Fascinated by this idea, Mr Tompkins put his forehead against the cold smooth surface of the mirror, and pushed forward.

"Let's pretend the glass has gone soft like gauze," thought Mr Tompkins, "so that I can get through. Why, it's turning into a sort of mist now, I declare! It'll be easy enough to get through...." And certainly the glass was beginning to melt away, just like a bright silvery mist. In another moment Mr Tompkins was through the glass, and found himself walking along a rather narrow canyon with steep grey stone walls. The walls of the canyon were covered with a large number of darkish shadows which Mr Tompkins mistook for some kind of desert plant.

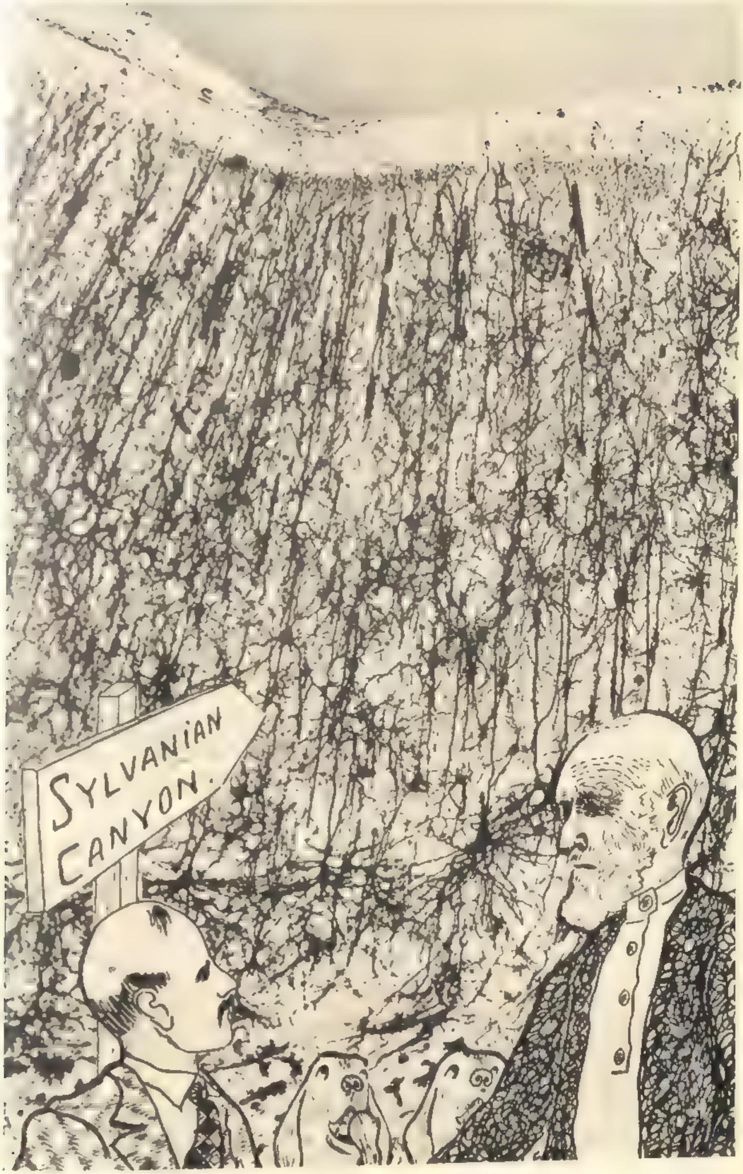
Suddenly he found himself surrounded by ten or fifteen loudly-barking dogs, all of different sizes and breeds.

"At least they are not as aggressive as my digestive enzymes!" thought Mr Tompkins. "But what on earth are all these dogs doing in my brain anyway?"

"Nazad, agolteleey!" shouted somebody behind him, and the dogs obediently backed away without touching him. Turning round, Mr Tompkins saw a very old man with a bushy white beard who was approaching him from the bottom of the canyon.

"Nitchevo, oni nehye koosayoutsia. Rad vas vidyet!" said the old man extending his hand, and—noticing the embarrassment on Mr Tompkins's face—continued, "Translated into English, I said 'Dogs don't bite. They are nice experimental dogs. Welcome to Land of Cerebrum'."

"Cerebrum", repeated Mr Tompkins. "Isn't that the learned name for the brain? Do you mean to say that I am actually inside my own skull,



VI. "*Nitchevo, oni nehye koosayoutsia*", said the old man

(Courtesy of Dr Frank George Young, University College, London)

and that these desert plants covering the walls of the canyon are the nerve cells which control all my memories, thoughts, and desires?"

"Right", said the old man. "You are at the bottom of what we call Sylvian fissure, deep gorge in the cerebral cortex originating at lower part of each brain hemisphere, and curving upward and back along its side. A great many of your sensory and motor centres are located in this region. As you see, each nervous cell, or *neuron*, has a number of branching tentacles or fibres running in all directions; they really do look like some fantastic desert plant when you think about it. Some of these fibres are comparatively short, serving as intercommunication lines between the several hundred million neurons forming your brain. Others are very long and run inside your spinal column to the most distant parts of your body, connecting brain with various sensory organs as well as with the muscles. Every bit of information obtained by your senses is sent into the brain through incoming nervous fibres known as *dendrites*. As soon as that information reaches the cerebral cortex, the central neuron council gets busy to decide what to do about it, and, when the decision is made, orders are sent to the muscles through outgoing motor fibres."

"Very much like the electronic machines with their input and output channels leading to the central computing unit", said Mr Tompkins. "I would like to see how it really works."

"That's very easy", said the old man leading Mr Tompkins to a large neuron embedded in the wall of the brain canyon. "This, for example, is one of your motor neurons. These branching tentacles are the receiving channels of the neuron, and are known as *dendrites*. That long fibre which goes all the way down the canyon is an *axon* along which signals are sent out to other regions. Now watch!" said the old man suddenly stamping his heavy boot right on to Mr Tompkins's pet corn. "In a minute you will see your own feeling of pain."

And indeed, Mr Tompkins could see an excitation seizing the entire slope of the Sylvanian canyon. His sensory centres had already received the danger signal from his toes, and were now asking his motor centres to

do something about it. A number of alarm signals were converging towards the neuron along its branching dendrites; they could be easily noticed by temporary discoloration of the fibres at the regions through which they were passing. When the incoming signals had finally entered the main body of the neuron, a long-distance impulse started outwards along the axon.

"It travels at about two hundred miles per hour," said the old man, "but of course you see it in different time scale. It probably just reaches its destination now."

"Ouch!" exclaimed Mr Tompkins suddenly, and jerked his foot from under the old man's boot.

"I did not mean to hurt you," said the old man with a smile, "but you told me yourself you wanted to see how your nervous system operates. This particular neuron is connected with your speech organs, and the signal you have just seen going out was sent to your vocal cords ordering them to produce a loud sound, presumably with the purpose of scaring away whoever was hurting you."

"And also to my foot, to jerk it away", added Mr Tompkins.

"No, you are wrong there. Such elementary action as that can be dealt with by lower parts of your neuron council. These comprise the spinal brain or spinal cord, which runs all the way down through your vertebrae. In fact, even if your head had been cut off, you would probably jerk your leg just the same. At least frogs do so. But, of course, without your head you could not possibly say 'Ouch'."

"But how does that neuron-council, as you call it, know what to do in each particular case?" said Mr Tompkins thoughtfully. "In the case of electronic machines all the wiring scheme of relays is conceived in the brain of the people who design them. But who designed the human brain itself? Mustn't we assume the existence of some super-being who conceived all these intricate connexions between the neurons in the brain?"

"It's a good question," said the old man, "and I can answer it, even though only in a general way. You must remember first of all that it takes

only a few years to build the most complicated electronic machines, whereas it took at least a billion years of organic evolution to develop a brain system as advanced as ours. As in any other evolutionary progress, the development here was carried forward by trial and error.

"You have quite rightly compared the neuron system of the brain with the system of relays in electronic machines, and what you call 'wirings' is known in biology as *synapses* between neurons. A synapse consists in establishing a contact between the endings of two fibres belonging to two different neurons. Many such connexions were established as a result of spontaneous mutations far back in evolutionary history, and, being found useful by the organism, were carried from generation to generation through regular hereditary processes and natural selection. You do not need to learn to jerk away your foot if it is hurt. That is known as an instinctive or innate reflex. But other more complicated actions, such as saying 'Pardon me' if you step on somebody else's foot, are not hereditary, and have to be learned from experience in each particular case. I call them conditional reflexes.*

"Take this Barbosik, for example," continued the old man, putting his hand lovingly on the head of a fine Irish setter sitting at his side, "he learned to recognize a certain musical note for the sake of food. For weeks and weeks my assistant played that note on his violin when Barbosik's food was served. Thus the signals sent by the taste-buds of his tongue to the taste-neurons in his brain arrived simultaneously with the sound signals coming to the auditory neurons, and a connexion between the two was somehow established. You may imagine that this simultaneous excitation of both neurons, which, as we know, is electric in nature, could produce some kind of conducting channels between their previously insulated fibres. And, once the insulation is broken through, the connexion becomes permanent, and the sound impulse is, so to speak, mistaken for taste-impulse. Since every dog, like any other animal,

* *Editor's note:* The original term *conditional* reflex introduced by the famous Russian physiologist, Ivan Pavlov, evolved into *conditioned* reflex in English scientific literature.

possesses an instinctive reflex which causes the salivary glands to secrete saliva as soon as the tongue feels the taste of food, Barbosik's mouth waters now each time he hears that note on the violin. Of course, it is only a small example, but I am quite sure that all our actions, even the most intricate ones, are based on such reflexes which are acquired either in the evolutionary history of the animal, or in the personal history of any given individual."

"You know," said Mr Tompkins, "I have read somewhere that they are now trying to make electronic machines learn things in exactly the same way. For example, one can set two machines playing chess against each other, by wiring-in the knowledge of the basic rules of the game, as well as that of several simple gambits and a few elementary tricks. Both machines are supposed to have large electronic memories, and if either of them loses the game through some stupid move, it will never repeat that move again under similar circumstances. Of course, they will play like imbeciles to start with, but after many games they are supposed to acquire such skill that even the chess champion of the world could be expected to lose to them."

"Very, very interesting", said the old man with a touch of admiration in his voice. "It seems they really begin now to build machines reminding us in their perfection of living organisms. And, indeed, both are built on very similar principles."

"Do nerve impulses travel along the fibres in the same way as an electric current runs through copper wires?" asked Mr Tompkins, encouraged by the last remark.

"They are similar, inasmuch as both are electric in their nature," said the old man, "but I would say that a nervous fibre is a much more ingenious device than the wire of an electric bell. In the latter, electric power is supplied by a battery in which different electrochemical processes are taking place. When you press a button, the battery pumps current through the wire and the bell rings as long as you continue to press. But, as soon as you break contact, the wire becomes electrically dead again.

Now, in the case of nerves, the battery is located so to speak all the way along the wire so that every inch of nervous fibre is at all times charged with electricity. You can think of such a fibre as a long cylindrical condenser charged with negative electricity on the inside, and positive electricity on the outside. When the nervous fibre is disturbed at one end, the positive and negative charges come together and the electric polarization in this section vanishes. This causes, however, a similar discharge in the neighbouring section, and then again in the next one....As a result, depolarization processes run along the fibre from end to end—just like a detonation running along the primer-cords used in high explosive work. The trick is, however, that as soon as the signal has passed through, in fact within one-thousandth of a second, the nervous fibre is again regenerated to its original polarized state by energy supplied from ATP-molecular bonds from the surrounding cells. Thus, nervous fibres can carry many hundreds of signals every second through all the long life of the organism. It is really about the most perfect communication system in the world, even though the speed of propagation is considerably lower than in the case of the man-built telegraph or wireless."

"But if the brain is essentially an electric circuit system," said Mr Tompkins, "doesn't it emit radio waves to the outside world? This would be an excellent explanation of such things as mind-reading, wouldn't it?"

"I don't know", said the old man cautiously. "There is, of course, a good deal of discussion on the subject of thought-reading, but I have not seen a single experiment yet which would confirm it with what I would call scientific accuracy. On the other hand, it would be quite unscientific to deny the phenomenon *a priori*.

"But it is certainly true, though much less exciting, that electric processes in the cerebral cortex show up outside the skull. In fact, if one presses electric contacts to two different points on the skull, one notices an oscillating electric potential with a period of about one-tenth of a second. That electric tension can be amplified by a system of vacuum tubes and recorded on a roll of paper. These particular brain waves are easily

Fig. 9. Brainwaves are recorded on a paper tape

noticeable when the person is asleep or is at least in a state of complete rest; they fade considerably as soon as the subject begins to think."

"Shouldn't it be the other way round, if thinking is an electric phenomenon?" asked Mr Tompkins in surprise.

"Not necessarily. You can imagine, for example, that in a state of rest

all the electric circuits in the brain are operating in unison, and thus collaborate in producing definite electric tensions on its surface. But, as soon as mental work begins, the neurons break step, and their effects on the skull cancel out. But we know too little yet about that phenomenon, and there is still a lot of work to be done in that direction."

Mr Tompkins was quite fascinated by this visit to his brain and, for the first time since he started these sightseeing trips through his own flesh, he began to feel that living matter, even though immensely more complicated than ordinary inorganic materials, is ruled by the same fundamental physical laws which govern all the other processes in the universe. Nevertheless, he was wondering how the terms like "consciousness", "soul" and "I" used by philosophers fitted into the picture he had seen with his own eyes.

"There is one thing that is bothering me", Mr Tompkins said, turning again to the old man. "I see very well now how *my* body, *my* heart, *my* lungs, *my* stomach, *my* muscles, *my* nerves, and even *my* brain operate. But who am *I*? It seems that I have never met *myself* inside my own body!"

"Oh!" said the old man, and smiled through his whiskers. "Let me answer your question by asking you a question. Suppose that in your city there appears a new fashionable Doctor *X* who claims that he has discovered the secret of rejuvenation. He establishes a clinic where he promises to restore youth to any person within a few weeks, and for a reasonable fee. At first people are very sceptical, but they soon find out that Doctor *X* really is as good as his word. There is the case of a Professor Emeritus of the local university, the well-known Dr *M*, who, after three weeks of treatment took back his old playing position in the university's football team. There is also the case of a society matron, Mrs *R*, who at her own request became so young that only her parents, but not her husband, could recognize her. There are also many other cases where the patients seem to lose a rather less striking number of years, yet who feel nice and vigorous after the treatment. But the treatment itself remains a mystery. After being accepted by the clinic the patients are immediately put to

sleep, and the first thing they know is that the bill and a mirror are presented to them on their way out of the clinic. Suppose you wish to take twenty or thirty years off your shoulders, and register at that clinic. But, this time something goes wrong, and, before you are put to sleep, you overhear a conversation between two nurses which reveals the method used by Doctor *X*. You find that what is being done is essentially the following. The clinic maintains, somewhere out in the country, a secret farm on which a great number of human babies, acquired by various semi-legal means, are being reared. These young people of different ages are developed according to the best medical standards in respect of all their physical abilities. But their brain is kept absolutely blank. When a new patient enters the clinic and states the age to which he or she would like to return, a young person of suitable age and appearance is selected from the farm. If necessary, plastic surgery is performed to make that 'brainless' body look exactly like old photographs of the patient in question. Now comes the most important part of the treatment, which is really creditable to the scientific achievements of Doctor *X*. Your new body and yourself are placed side by side on a hospital bed, and by an intricate electronic system all the synapses existing between the neurons in your brain are copied into the brain of the younger person. In principle, you see, it is quite possible. Thus you get an identical twin who, though younger than you, possesses all your memories, all your knowledge, and all your other mental characteristics. Well, after that they kill your old body one way or another, and it is disposed of, while the new body, looking and behaving exactly like yourself, is released from the clinic to your family and friends."

"But that's cheating!" exclaimed Mr Tompkins. "A doctor like that should be sent to jail!"

"Don't get excited", said the old man. "After all that is only an imaginary case. It is quite true that the existing laws would consider such practices as criminal. But let us think about it for a moment. Suppose Doctor *X*'s discovery to consist in a method by which the cells in your body could be replaced by new cells *one by one*. This isn't much different

from ordinary blood transfusion, is it? But I am not speaking about the legal aspect of the problem, and give it to you only to ask a question. After finding out what Doctor X is going to do to you, would you or would you not run out of that clinic and never, never, come back?"

"I certainly would!" said Mr Tompkins with conviction.

"Now you are being irrational", said the old man with a smile. "If you consider *yourself* as not being the collection of material cells of your body, but rather as a complex of your abstract memories, thoughts and desires, why should you object to the transference of all the contents of that inner self to a new material background? After all, nobody could object to transferring the contents of an old note-book into a new and better one, if all the information is copied without any change."

"I suppose you are right," said Mr Tompkins, "and I think I ought to have gone on with that operation. But, in fact, I don't think I would."

"Well, when you finally make up your mind about that question," said the old man, "you will probably know your attitude towards the philosophical questions you are worrying about."

"It is almost as bad as psychoanalysis", said Mr Tompkins who was beginning to feel that his mind was swimming. "Now I am getting completely confused."

"Speaking of psychoanalysis," said the old man, "there is a lot of bluff in it, but there are also many points that are certainly based on the real physiology of our head-brain. For example the notion of *suppressed memories* introduced by Sigmund Freud is most probably connected with the short-circuited neuron chains in the cerebral cortex. Memory signals are going round and round causing a constant disturbance in your brain until they are brought out and dealt with in a rational way."

"Do you think I might have such suppressed memories too?" asked Mr Tompkins. "This is a good opportunity to straighten these things out."

"Tell me," said the old man looking him straight in the eyes, "is there anything that troubles your subconscious? Anything you are afraid of without any apparent reason?"

"There is", said Mr Tompkins. "I hate to sit on hard chairs. And whenever I sit on a soft one, I inevitably fall asleep. Do you think the fear of hard chairs could have something to do with the suppressed unpleasant memories of my childhood?"

"Possibly", said the old man, leading him through the labyrinth of neurons. "There seems to be a great noise going on over there. Let's investigate. Perhaps that's why you hate hard chairs."

When they entered the part of the brain indicated by the old man, the noise rose to such an intensity that Mr Tompkins was quite unable to hear his own thoughts. The dendrites and axons connecting the neurons were singing in unison like telegraph wires in a high wind.

Listening carefully, Mr Tompkins was able to recognize the high voice of his dear old mother through the din.

"You bad boy", she was saying. "How many times have I told you not to touch that jar of strawberry jam in the kitchen! Bring me my hairbrush, and put down your pants."

"I won't do it again Mummy!" pleaded Mr Tompkins. "I promise I won't."

But it was too late, and the terrible brush was coming down at him, like an angel of vengeance....

"Ouch!" shouted Mr Tompkins as thousands of sharp pins shot into his tender skin. "Ouch!"

"What's the matter?" The young mathematician, attracted by Mr Tompkins's screams, rushed out from the storage room. "Have you hurt yourself?"

"I won't do it again, I promise," said Mr Tompkins, rising from the flattened box.

"Oh, that's where they were, and you've squashed them!" exclaimed the mathematician, looking ruefully at the pile of broken glass. "A bideʒ lo!* Now we'll have no memories until the next delivery on Wednesday."

* *Editor's note:* "A bideʒ lo" is an untranslatable oath in Maniacal language, appearing on the outgoing tape every time something goes wrong with the machine.

"I am very sorry", said Mr Tompkins, trying to brush the sharp glass fragments from the seat of his trousers. "But *I* shall have memories for a long time to come. I'll have to sleep on my stomach for the next few nights."

"Well, accidents do happen," said the mathematician philosophically. "But I hope you have learned something by coming here."

"I certainly have", said Mr Tompkins reaching for his hat and coat. "Good night, and thank vou very much."

IV. The Professor's Lecture

THE NATURE OF LIFE

"So you are interested in biology", said the old Professor, who had come for dinner with his daughter and son-in-law. "Why don't you come to my lecture tonight? I am going to speak about the relation between the phenomena of life and the laws of physics."

"I didn't know you were interested in biology as well, father", said Maud, refilling his coffee cup. "I thought your field was limited to atoms, atomic nuclei and that sort of thing."

"That's true," said the Professor, "but during my recent visit to England I met an old friend of mine, a celebrated Austrian physicist who once made a basic contribution to the Quantum Theory. Now he is all wound up about the fundamental problems of biology, and thinks that it's just the time for physicists to *cut in*. In fact, this *maladia biologica*, as some people call it, seems to have spread far and wide among the physicists, both theoreticians and experimentalists. And, instead of following the latest views of Dirac about the existence of light-ether, or measuring the number of delayed fission neutrons, many of them devote all of their time to breeding bacteria or cutting open the tummies of white mice."

"Does it mean that there is nothing left for a physicist to do in his own field?" asked Maud with a smile.

"Hell, no!" said the Professor, "there is still a lot to do in pure physics, especially in the new field of elementary particles. The point is, however, that biology, which until recently was a purely descriptive science, is now rapidly developing into an exact discipline. That stage, which every branch of science reaches sooner or later (depending on the complexity of the field of its studies), is characterized by the discovery of the basic elementary processes which underlie the apparent complexity of macroscopic phenomena. If you look into the state of physical knowledge about a century ago, you will find that it was essentially composed of a large

quantity of seemingly unrelated information concerning the mechanical, chemical, thermal, optical, electrical, magnetic, and other properties of material bodies; a kind of classified directory, I would say. With the establishment of molecular and atomic theories, and with the progress of our inquiry into the internal structure of individual atoms and their nuclei, the situation has changed quite a lot, and we are now able to reduce the multitude of complicated large-scale phenomena to the motions and interactions of the constituent particles from which all material bodies are constructed. We find, indeed, that the laws governing these elementary phenomena are comparatively few and rather simple, so that the entire structure of physical science can be based on a limited number of fundamental notions and laws, much in the same way as the system of Euclidean Geometry is based on a few fundamental definitions and axioms. We have dug here to the very bottom of the complicated structure which faced the earlier explorers.

"Biological phenomena, which are immensely more complicated than the processes taking place in inorganic materials, represent, of course, a much more serious challenge to the human mind, and it is no wonder that progress in that field is much slower. It seems, however, that just now we are on the verge of a great advance. The *Cell Doctrine* (which states that all living organisms are nothing but large and ingeniously organized colonies of individual cell-units), can be compared, in a sense, with Dalton's atomic hypothesis in physics and chemistry. The discovery of *genes* and *viruses*, which display all the characteristic properties of living organisms, being at the same time nothing but complex chemical molecules, brings us to the very basis of biological simplicity. In a sense, one could compare these simplest living beings with the elementary particles of modern physics. Once we learn the laws of their behaviour (and they do seem to obey comparatively simple laws) we should be able, at least in principle, to understand the more complicated behaviour of composite living organisms. We should be able, in fact, to solve the ancient riddle of the nature of life."

"But", asked Mr Tompkins, who had listened with fascination to this discourse by his famous father-in-law, "why don't you let the biologists handle all these problems by themselves? Why should physicists cut in?"

"Because", put in Maud gingerly, "physicists' eyes are bigger than their stomachs."

"No! Or, at least not quite", retorted the Professor, with an irritated glance at his daughter. "The point is that studies in this direction will require a great deal of mathematical knowledge, and skill in handling complex theoretical problems. Since in physics similar situations have existed for centuries, all physics students get a solid mathematical education, and even future experimentalists are required to take advanced mathematical courses. I dare say that even chemists possess, nowadays, a good knowledge of mathematical methods. On the other hand, a student of biology leaves the university with no more mathematics than he got in the high school. Or even less, since he will probably have forgotten how to solve a quadratic equation, or a rectangular triangle. So physicists, particularly theoretical physicists, must temporarily fill the gap, until the time when differential equations and wave mechanics are taught to young biologists along with cytology and neurology."

"But", he interrupted, "it is nearly eight o'clock and I must hurry to my lecture. I hope, my dear daughter, you will excuse your husband from drying the dishes tonight."

* * * * *

The great university lecture hall was almost filled with young students and older men—apparently the faculty members, physicists and biologists—who had come to learn about the relationship between their sciences. Mr Tompkins spotted a vacant chair near the window and sat down, grimly determined not to fall asleep, but to listen to the lecture from

beginning to end. Even though the chair was rather narrow and hard he felt quite comfortable, since his allergy to hard furniture had completely gone after his recent psychoanalytical treatment.

"Ladies and gentlemen," began the Professor, "the problem of life has always been, and still is, the foremost challenge to the mind of any thinking man. Ever since people began to wonder what was the difference between life and death, there have existed two opposing schools of thought: the *vitalistic* and the *mechanistic*. The former school, which not so long ago was the largest, but is now rapidly shrinking, thinks of the phenomenon of life as something entirely different from the phenomena observed in the inorganic world. The difference is supposedly due to a mysterious force of life, or *vis vitalis*, which is present in all living organisms, and is responsible for all the differences between living and non-living matter. The supporters of this school consider it fundamentally impossible to explain the properties of living creatures on the basis of purely physical and chemical interactions.

"The mechanistic point of view is the exact contrary: that all phenomena observed in the living organism can be reduced in the end to regular physical laws governing the atoms of which that organism is constructed, and that the difference lies entirely in the relative complexity of living and non-living matter. According to this point of view, basic manifestations of life like *growth*, *motion*, *reproduction*, and even *thinking* depend entirely on the complexity of the molecular structures forming living organisms, and can be accounted for, at least in principle, by the same basic laws of physics which determine ordinary inorganic processes.

"The first, and the most important argument which must be settled by a purely physical theory of life concerns the problem of entropy-changes in living organisms. In fact, it would seem at first sight that all living organisms defy one of the most fundamental laws of physics: The Law of Ever-Increasing Entropy.

"What is entropy, and why is it supposed to increase? To answer this question, I must first remind you that all material bodies dealt with in

physics are composed of an immense number of individual molecules involved in violent thermal motion. The air in this room is nothing but a swarm of oxygen, nitrogen and carbon dioxide molecules rushing wildly in all directions and colliding all the time with each other and with the walls of the room. The water molecules in the glass on my lecture table are loosely glued to each other by intermolecular forces, so that their thermal motion is like the aimless crawling of tightly packed worms in a fisherman's can. The molecules forming the piece of chalk which I hold in my hand occupy fixed positions, making chalk a solid body, but even they are involved in a wild thermal dance, jerking and swinging around these positions.

"The most characteristic feature of thermal motion is its lack of order, its state of elementary disorder, as the physicists call it. The higher the temperature, the higher the disorder of molecular motion. At a comparatively low temperature there is at least some order in the distribution of molecules in space (as is shown by the crystal structure of solids), even though the vibrations around their positions of equilibrium take place quite at random. In a liquid state individual molecules are at least held together within a fixed volume even though they may easily glide along each other. In the gaseous state, which is reached at still higher temperatures, the last trace of order in spatial location is lost. So you see that the degree of molecular disorder increases with the total amount of heat within the body. More heat means more intensive thermal motion, and more intensive thermal motion means increasing molecular disorder.

"However, even for a given temperature, one can imagine different degrees of orderliness in thermal motion. Thus, for example, one can imagine that one-third of all the air molecules in this room move vertically up and down between the floor and the ceiling, one-third horizontally from the front wall to the rear wall, and the remaining third also horizontally between the wall on the right and the one on the left. This is shown for a two-dimensional case on the left of my first slide. [*Slide please.*]

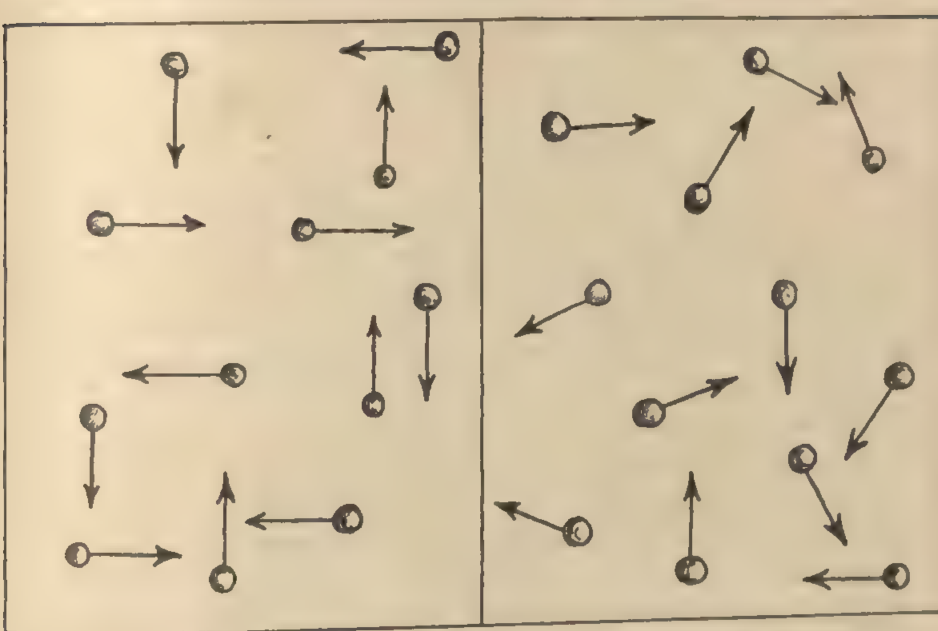


Fig. 10. Ordered and orderless motion of molecules in a gas

"One can easily understand that such a peculiar velocity-distribution of molecular motion is extremely unlikely, since, indeed, mutual collisions between the molecules tend to scatter their velocities in all possible directions. Yet the possibility of such a distribution is not completely excluded, and there is always a chance that it may actually take place once in a long while and for a brief moment. However, you would not bet on such a chance any more than you would bet on the chance of throwing a few hundred heads in succession while tossing a coin.

"Between this well-ordered velocity distribution and a completely orderless or random distribution (shown on the right side of the slide) lie the distributions with intermediate degrees of randomness.

"The degree of disorder, of randomness of molecular motion, is measured in physics in terms of entropy, which is defined simply as the logarithm

of the probability ascribed to any particular type of motion.* So the highest value of entropy is given the most probable, completely orderless, motion, while types of molecular motion showing some degree of order are given lower entropy values.

"The law of increasing entropy simply states that the natural tendency of events is to proceed from less probable (ordered) distributions to more probable distributions with various degrees of disorder. This must sound quite natural to all of you. Indeed, every housewife knows that, while it takes any amount of work to keep a house in order, no effort is needed to make it untidy; you just stop doing anything about it for a day or two. Every highway commissioner knows that no maintainance equipment is needed to make the roads impassable....And every army officer knows that, for all the effort which must be spent in training soldiers to march in step, they easily turn into a mob as soon as discipline is broken....

"If the law of increasing disorder did not hold for thermal motion in material bodies, some most unusual engineering feats would be possible. If one could 'persuade' the molecules of air to assume sufficiently often the three directional velocity distribution I have described, one could build jet planes which would fly without any fuel. Indeed, one-third of all the molecules moving in the same direction would form a perfect 'natural' jet. We should also be able to construct a fuelless car which sucked in the orderless heat-motion from the surface of the road (and every road surface is very hot as compared with absolute zero) and 'straightened it out' into an orderly motion of wheels. Such cars would also help to make town streets more comfortable in summer, since they would cool the pavement by sucking the heat out of it....However, such machines, though com-

* *Editor's note:* The Professor failed to mention the reason why the logarithms of probabilities and not the probabilities themselves are used. The point is that the probabilities of different states of molecular motion vary between very wide limits, being often different by factors containing tens and hundreds of decimal places. Using (decimal) logarithms, one finds that corresponding entropies will differ only by ten or a hundred units—making their handling more convenient. It should be also mentioned that, in conventional thermodynamics, it is customary to multiply logarithms of probability by a certain numerical factor k known as Boltzmann's constant.

pletely consistent with the law of conservation of energy, cannot be built because they would violate the law of ever increasing entropy. They are often called perpetual motion machines of the second kind, the phrase 'perpetual motion of the first kind' being reserved for machines violating the conservation law. I am sorry to have taken so much time on the subject of entropy, but I hope at least that I have managed to make it reasonably clear to you.

"Now we return to the question of the alleged violation of the entropy law by living beings, where things seem to go just the opposite way. For example, you put a seed into the ground and a great oak grows out of it. The complex organic molecules constituting the body of the oak are made up of the atoms which previously formed the molecules of carbon dioxide absorbed by its leaves, and the molecules of water and a few simple inorganic salts sucked in by its roots. We have here a transformation from the simple molecular structures of air and water-solution of salts into a highly organized structure of protein molecules and plant cells. There is no doubt that the second structure is *per se* much more ordered than the earlier ones, and that entropy had decreased in the process of growing.

"'That is that!' a vitalist would say. 'This definitely proves that we must introduce a notion of *vis vitalis*, an organizing force of life, which opposes the tendency to disorder of inorganic materials. As long as this *vis vitalis* is present in the body of a plant or an animal, its development goes against the laws of ordinary physics. But as soon as death comes, and the *vis vitalis* flies out of the body like a white dove, the laws of physics come into force again, and the organic matter rots and decays into its primary elements.'

"This argument seems very persuasive indeed, but wait a minute. Is there nothing else absorbed by a growing plant except carbon dioxide, water and salts? What about sunlight, without which no plant can grow? Of course, nobody would deny that the sun's rays bring in the energy which is necessary to build complex organic molecules out of the much

simpler molecules of carbon dioxide and water. As the plant grows, solar energy is absorbed and stored in its body. It can be liberated again when we use the plant as firewood, or when the plants, used as food by animals, serve as the sources of mechanical energy. This is, in fact, the background of the well-known statement that a horse is an atomic-powered motor since it gets its energy from eating grass, the grass received the energy from the sun's rays, and solar radiation is maintained by thermonuclear reactions taking place in the sun's interior. [*Slide please.*]

Fig. 11a. Energy and negative entropy pull a wagon

(*Borrowed from an article by Professor J. A. Hynek, who borrowed it from the author's* Atomic Energy in Cosmic and Human Life.)

In the case of a farmer, whose diet includes both vegetables and meat, the situation is slightly more complicated, as indicated on my next slide. [*Slide please.*]

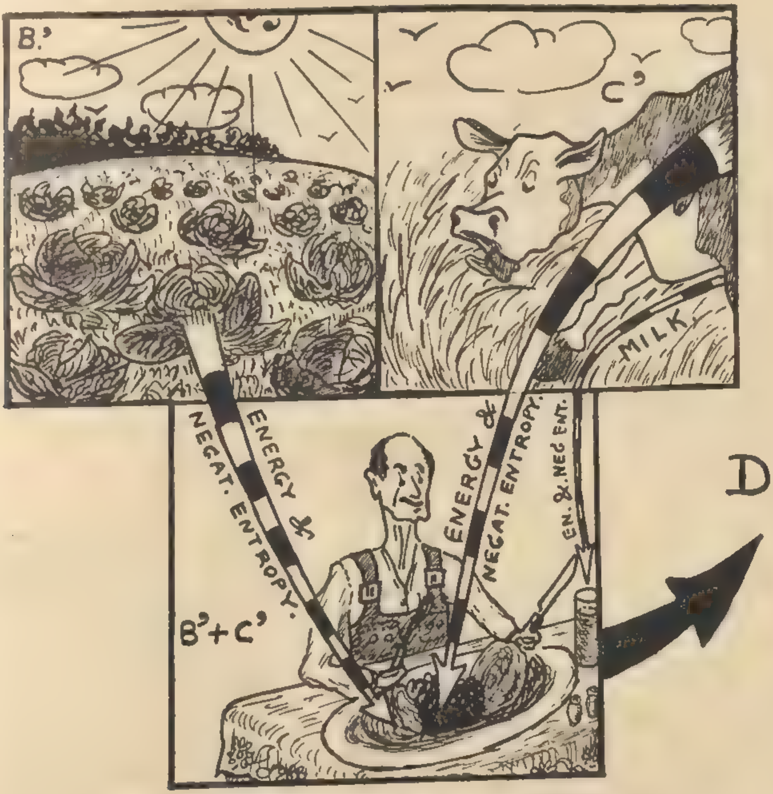


Fig. 11b. Energy and negative entropy feed a farmer

But can the sun's rays also account for the increasing molecular order, or the decreasing entropy which characterizes the growth of a plant? Any physicist, whom you ask this question, will say yes. He will tell you, in fact, that solar radiation, reaching the earth, shows a very high deficiency of entropy content, and that plants are welcome to use the entropy-deficiency of solar radiation in order to reduce their own entropy. To

understand that important point, we have to learn a little more about the physical properties of thermal radiation, which is an immediate result of the thermal motion of the molecules composing any material body. No matter how cold the body is (except of course at absolute zero) it gives off a certain thermal radiation with a certain prevailing wave-length. As the temperature of the body increases, radiation becomes more intensive, and its prevailing wave-length becomes shorter. A piece of ice gives very little heat, so that when you stand near an ice-block you feel cool because your skin radiates more heat into the ice than the ice radiates into you. On the other hand, a stove, having a higher temperature than your body, emits more thermal radiation than your skin does and you feel a pleasant warmth coming from it. As long as the temperature remains below 800 degrees centigrade, the wave-length of radiation is too long to affect the retina of your eyes so that you do not see, but just feel it. It is often called, incorrectly, 'heat rays'. With an increase in temperature the prevailing wave-length decreases, and the radiation becomes 'visible'. You will see the heated body first as red-hot, then as yellow-hot, white-hot and finally blue-hot. In my next slide [*slide please*], I have plotted energy-distributions in the thermal radiation spectrum for different temperatures of the emitter. I need not explain the details of the slide, since it speaks for itself. But I want to draw your special attention to this fact: that for any given temperature there is a well-defined spectral distribution, and also a well-defined total intensity, or the amount of radiation energy per unit volume. The observed properties of thermal radiation can be derived theoretically from the assumption that the *light vibrations are taking place completely at*

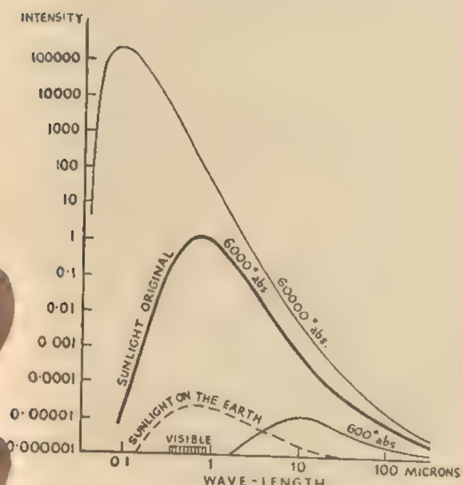


Fig. 12. Energy spectrum at different temperatures

random both in their directions and amplitudes. This assumption is identical with the one concerning the randomness of molecular motion in a gas. Thus, just as in the case of a gas, the normal state of thermal radiation is that of *elementary disorder* and its entropy has the maximum value.

"However, this statement holds only as long as the thermal radiation is in immediate contact with the surface of the hot body from which it is emitted. As the radiation from the sun's surface spreads out into the surrounding space it is rapidly diluted, and its energy density decreases in inverse proportion to the square of its distance from the sun. Since the distance from the sun to the earth exceeds the radius of the sun by a factor of 214, solar radiation reaching the earth contains 46,000 ($=214^2$) times less energy per unit volume than it did while leaving the photosphere of the sun. This decrease of energy-density is not accompanied, however, by corresponding changes in spectral distribution, since while travelling through the empty space between the sun and the earth, the radiation does not have any chance to exchange the energy contents between its different wave-lengths.

"Thus, solar radiation reaching the earth is in some kind of *hybrid* state, possessing a spectral distribution which corresponds to the very high temperature of the solar surface (6000° C.), and the energy-density corresponding to the much lower temperature of a hot sunny day. One can easily show that such a state of affairs is not at all a 'most probable' one, or that, in other words, the entropy of solar radiation reaching the earth is not at its maximum. This does not mean, however, that the entropy of sunlight decreases as it travels towards the earth, since, in fact, such a decrease would violate the law of entropy. What actually happens is that solar radiation, which is expected to gain in its entropy while travelling away from the sun, does not gain enough. The case is similar to the case of a tax-payer who finds that his income during the year was less than the amount he put into his declaration of the estimated tax at the beginning of that year. Well, one way or other, sun-rays falling on the surface of

green leaves, can so to speak, suck out the excess entropy, thus helping to bring down the total entropy content of the plant. Of course, the process would not necessarily go on of itself, and it is up to the plant to use the opportunity of getting negative entropy from radiation. In the same way in the business world, a 'financial opportunity' would not necessarily enrich a person unless he is smart enough to seize it. When solar radiation carrying the opportunity to reduce entropy falls on the iron roof of a house, the opportunity is simply lost because iron is 'too stupid' to know how to use it. The roof will be heated and will send back solar radiation in the high-entropy form of heat rays. But the plants are smart in that way, and use a special process known as *photosynthesis*, which utilizes both the energy and the entropy-deficiency of solar rays for building up complex organic structures from much simpler inorganic ones.

"Some of you may object to this theory that entropy-deficiency or negative entropy is used by growing plants, since it would seem at first sight that deficiency of something cannot be helpful for anything, and that getting something negative cannot be used for doing something positive. But if you think for a moment you will see that it is just the result of terminology, the result of our original definition of entropy as a degree of disorder and not a degree of order. In fact, the statement that entropy-deficiency in absorbed radiation is necessary for plant life, is similar in its substance to the statement that arsenic-deficiency in absorbed food is necessary for the life of human beings. I hope you see what I mean. Well, if we look again at the one of my previous slides [fig. 11 *a*] which represents the sun-grass-horse system, you will notice white arrows which indicate the entropy deficiency, or negative entropy, which originates when solar radiation travels towards the earth, and is later handed down the line in order to keep spick and span the complex organic structures forming the grass and the horse.

"Summing up our discussion, we can say that the old metaphysical idea of *vis vitalis* can be given by the following simple physical interpretation:

$$\begin{aligned}(\textit{vis vitalis}) &= (\text{entropy deficiency})\\ &= -(\text{entropy})\\ &= -k\,.\,\log\,(\text{probability of material structure and motion}).\end{aligned}$$

"Most of the entropy (and energy) collected by plants from the sun's rays goes to waste when the plants die and rot, but when a horse or a cow eats grass, or when we eat salad, the entropy-deficiency of the plant serves to reduce the entropy of animal tissues. And of course, when we eat a steak, we are getting the necessary entropy-deficiency second-hand or rather, third-hand in a somewhat more digestible, or at least in a more tasty form. My Austrian friend likes to say that in modern and scientifically organized restaurants the menus must not only include the columns of prices, and calories (energy content), but also an additional column telling the customer how much entropy they can get rid of by eating different dishes.

"Having settled the most fundamental problem concerning the relation between the phenomena of life and the laws of physics, we must now inquire into the details of the photosynthetic process which permits plants to collect the energy and the entropy-deficiency of solar radiation, and to send it down the line into the animal world. It must be said that, in spite of the tremendous amount of work done on this subject and the thousands of papers published on its various aspects, we are still very far from a complete understanding of the photosynthetic process. Yet, especially through the advances made during the last few years, we are beginning to get some glimpses of how this 'biggest construction project on the earth' is actually operating.

"It was known for a long time that the main agent in performing the marvellous trick of turning water and carbon dioxide into complex organic materials with the help of light, is the green substance called *chlorophyll* which gives all plants their characteristic colour. Microscopic examinations of plant leaves show that each cell contains green particles known as *chloroblasts*, which, in their turn, consist of still smaller units known as

grana. These grana, which are apparently individual conversion factories of solar energy, contain chlorophyll, and presumably a task-force of enzymes which help the chlorophyll to do its job.

"From a chemical point of view, photosynthesis is a reversal of the process of respiration or ordinary burning. In fact though, while—in the process of burning—complex organic molecules, formed essentially by carbon and hydrogen, react with atmospheric oxygen, liberating energy and forming simple molecules of carbon dioxide and water, the photosynthetic process puts together the molecules of atmospheric carbon dioxide and ground water, adds the energy from sun-rays, and produces complex organic molecules of sugars, starches, and cellulose, liberating the excess oxygen into the atmosphere. But, whereas the burning process easily goes on of its own accord, since it represents the natural direction of chemical reactions, photosynthesis must go, so to speak, uphill. To build organic materials in that way it is necessary to detach the hydrogen atoms from the oxygen atoms in water molecules, and to attach them, in proper proportions, to the molecules of carbon dioxide. Since breaking the chemical bond between hydrogen and oxygen in water requires more energy than one gets back when a hydrogen atom attaches itself to carbon, the process requires external energy, and is, as chemists say, *endothermic*. Since the organic substances formed in the process have a more elaborate structure than air and water, the process also requires the injection of negative entropy. Both of the elements needed are, of course, supplied by sun-rays.

"In order to get a rather clearer picture of how sun-rays do the job of transferring hydrogen atoms from one molecule to another we must remember that, according to our present physical knowledge, any kind of radiation consists of individual packages of energy known as *light quanta*. The energy of a single light quantum is proportional to its frequency, and is, in fact, given numerically by the product of that frequency and the so-called quantum constant. Red light, which is strongly absorbed by chlorophyll and is apparently the main agent of photosynthesis, has quanta with

an energy content of about 1·9 electron volts.* In order to move one hydrogen atom uphill from its position in a water molecule to that in carbon dioxide 1·3 electron volts are needed. Experiments show that in the process of photosynthesis two light quanta are absorbed for each hydrogen atom moved. Thus out of each 3·8 electron volts of the radiant energy of sun-rays, 1·3 electron volts are turned into chemical energy in plant material; an efficiency of 35 per cent, which surpasses anything that can be achieved in the inorganic world. A schematic picture of the photosynthetic process is given in my next slide. [*Slide please.*] You notice that

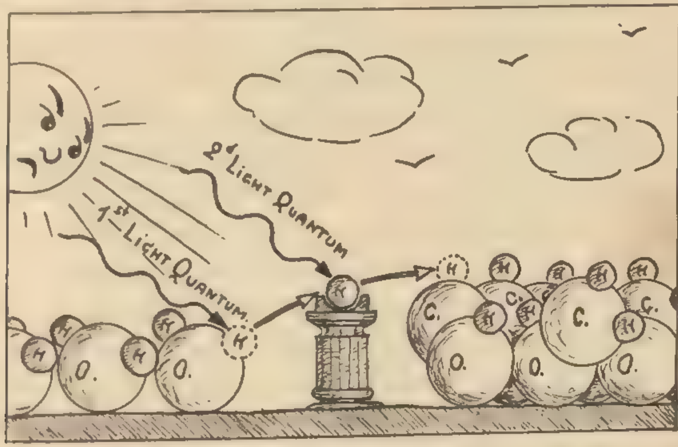


Fig. 13. Photosynthesis

chlorophyll, symbolized by a Doric pillar in the centre of the picture, serves essentially as an intermediate resting point for hydrogen atoms on their way from water molecules (the supply side, on the left) to the complex organic molecules (the construction side, on the right). The first light quantum kicks hydrogen from the water molecule and deposits it in the cavity on the top of the chlorophyll pillar, where it rests for a while, until

* *Editor's note:* One electron volt is defined as the energy acquired by an electron accelerated in the electric field of one volt. This unit was originally introduced in nuclear physics where energies are usually measured in millions of electron volts. But it can be also conveniently used in ordinary chemical reactions in which energy liberation usually amounts to only a few electron volts.

the second quantum brings it still higher into the proper location on the organic molecule under construction. If this intermediate resting place were absent the process would have been absolutely impossible. Organic molecules constructed by the photosynthetic process are known under the general name of *carbohydrates*, since they contain oxygen and hydrogen in the same proportion as water; in chemist's shorthand these compounds are written as $C_mH_{2n}O_n$. Thus the common sugar which you use with your coffee is written as $C_{12}H_{22}O_{11}$, whereas the formula for starch used to stiffen your dress shirt looks like $C_6H_{10}O_5$. Cellulose, which is one of the most important materials in plant structure, has the same chemical constitution as starch, but its molecules are arranged in a different way. Further, the chemical reactions taking place between these energy-rich and entropy-poor compounds lead to the formation of all other complex organic molecules, in particular those of protein, from which all plant and animal bodies are constructed.

"Although the scheme given on my slide gives a general idea of the photosynthetic process, its details are still not disentangled; in particular we know next to nothing about the enzymes which make that process possible. And it goes without saying that no one as yet has been able to repeat that process under laboratory conditions (or *in vitro*, as chemists say). It should also be mentioned that the *light reaction* described above represents only a part of the story, and is followed by the so-called *dark reaction* which is independent of illumination. In fact, if one illuminates a plant by a very short flash of light, using a device similar to that employed by press photographers, one notices that the liberation of oxygen started by the flash continues for about two-hundredths of a second in the darkness that follows. This time is apparently taken up by the dark part of the photosynthetic process, during which time the intermediate products formed by the action of light take part in more 'ordinary' chemical reactions. The presence of the dark reaction also accounts for the fact that the speed of photosynthesis, which at first increases in direct proportion to the strength of illumination, reaches a maximum at a certain

light intensity, and remains unchanged by a further increase of light. This is apparently the point at which the dark reaction operates at its maximum capacity, so that no further increase in the final result can be achieved by further speeding up of the first step.

"At this point I should like to stress that, besides their photosynthetic ability, all plants also possess a respiratory mechanism similar to that of the animals. In fact, photosynthesis in plants should be compared with the feeding of animals, and takes place only when food, in this case sunlight, is available. The respiration of plants takes place all the time, just as with animals; and during the night, when photosynthesis stops, respiration forms the main part of their biochemical activity.

"Before we leave the important subject of photosynthesis, I should like to mention that, although chlorophyll is undoubtedly the main substance used in photosynthesis by the plant world, it has its competitors. Thus, for example, some bacteria inhabiting sulphur springs contain, instead of ordinary green chlorophyll, a purple pigment known as bacterio-chlorophyll. This pigment also functions under the influence of sunlight; but, instead of breaking up water molecules as ordinary chlorophyll does, it breaks up the molecules of hydrogen sulphide (H_2S), thus liberating sulphur instead of oxygen.

"There also seem to be some bacteria which can grow without any light at all, using energy and negative entropy from certain inorganic compounds dissolved in water. But in this case too, the excess energy and the entropy deficiency of the chemical compounds used by the bacteria can be traced back to the original sun rays.

"A few words now about the general balance of organic energy on the earth. It has been estimated that out of the $4 \cdot 10^7$ kWh, representing the total amount of solar energy which falls yearly on the surface of the earth, $1 \cdot 7 \times 10^{15}$ kWh, or about half of one per cent, is stored by plants in the process of photosynthesis. Incidentally only one-tenth of that amount is due to land plants, the other nine-tenths being accounted for by algae in the ocean. In terms of weight, plant life converts yearly $1 \cdot 6 \times 10^{11}$ tons of

carbon from atmospheric air into organic compounds. Most of that amount is returned to the atmosphere, through the process of plant respiration, the rotting of fallen leaves and trunks, occasional forest fires, and so on. Only one per cent of synthesized material is used by the population of the earth as vegetable food, and another one and a half per cent as the food of domestic animals. One per cent more is used by humans as firewood, both for domestic heating and for industrial purposes. In my next slide [*slide please*], based on the data of the U.S. Government survey,

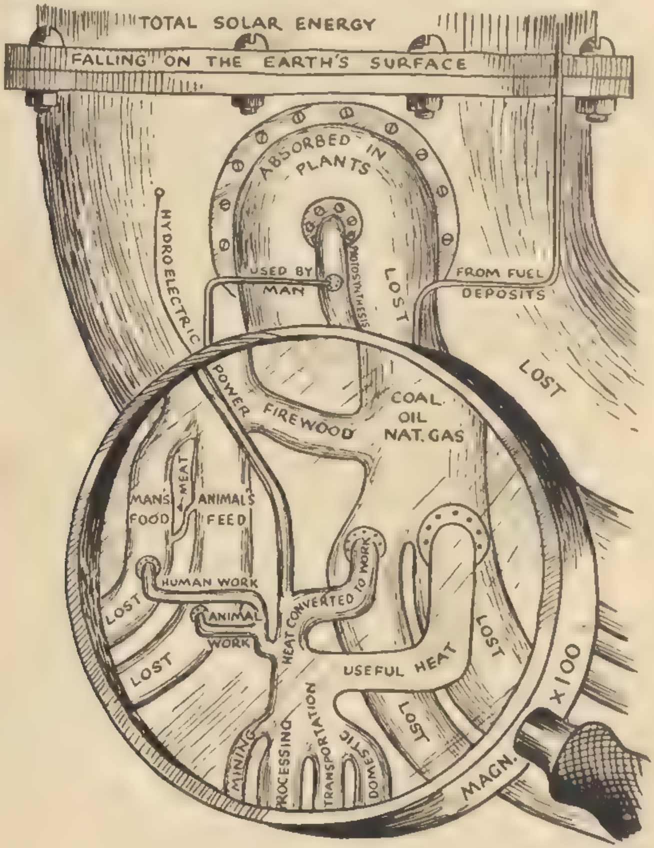


Fig. 14. The division of solar energy

the flow of solar energy and its subsequent distribution is represented in the form of a pipe system. The large incoming pipe carries the total flow of solar energy falling on the surface of the earth, the intermediate pipe carries the energy absorbed by plants, and a still smaller one the energy stored by the process of photosynthesis. The fraction of stored energy which is utilized by humanity is represented by a tiny pipe branching to the left; it is so thin that in order to see the details of further energy partition we must use a lens with a magnifying power of one hundred. Looking through the lens you see that this pipe separates into three branches corresponding to human vegetable food, animal food, and fire-wood. Incidentally, a narrow connexion leading from animal food to human food represents the average meat diet, mostly fish, of the human population of the earth. The firewood branch empties into a larger pipe which represents the energy obtained yearly from coal, oil, and natural gas. These irreplacable energy resources were made available to us by the photosynthetic activity of plants during geological eras long past. Now we come to the conversion of all these energy streams into useful work and useful heat, the processes in which we sustain terrific losses. The pipes which carry useful energy look very thin even through the lens. We have here $2{\cdot}1 \times 10^{12}$ kWh of useful heat, $1{\cdot}2 \times 10^{12}$ kWh of heat converted into mechanical work, $0{\cdot}2 \times 10^{12}$ kWh of human manual work, and $0{\cdot}1 \times 10^{12}$ kWh delivered by draft animals. A tiny pipe leading directly from the main stream of solar energy carries $0{\cdot}2 \times 10^{12}$ kWh of hydro-electric power. The total useful energy of $2{\cdot}9 \times 10^{12}$ kWh is distributed mainly between industrial processing ($1{\cdot}8 \times 10^{12}$ kWh), domestic uses ($0{\cdot}8 \times 10^{12}$ kWh), and extraction of raw materials ($0{\cdot}3 \times 10^{12}$ kWh). I have shown you this slide, even though it has little relation to the basic problems of life, simply because it is really very instructive and gives us a clear picture of our position in the living world.

"Returning to more fundamental questions concerning the physical theory of living processes, I would like to say a few words about the origin of life on our planet. It seems, indeed, that life originated on the

earth as soon as its surface cooled enough to make life at all possible. It also seems that life exists in other worlds whenever physical conditions permit. At least, recent studies of an American-Dutch astronomer have made it quite certain that vegetation, and maybe also simple forms of animal life, exist on the surface of Mars which in respect to its surface conditions represents probably the nearest analogy to our earth. So we may conclude that the appearance of life should not be considered as being due to some extremely improbable play of chance, but is in fact a fairly natural phenomenon to be expected in any place where the physical environment is favourable to its existence.

"What are the first steps in the basic transformation of non-living materials into living matter, and why did that process which took place during the early days of our planet not repeat itself again and again during at least one thousand million years of subsequent organic evolution? In fact, the continuity of organic evolution, as revealed by the studies of palaeontology, seems to indicate that all forms of life existing on the earth at present can be traced back to primordial protoplasm which first appeared in the precambrian ocean, and that no spontaneous creation of living matter has ever taken place since that early time. One way of answering the question is to say that the primitive oceans must have contained in solution various inorganic carbon compounds which evolved into more complicated organic compounds through a rather lengthy building-up process probably connected with the action of sun-rays, and that, once these original chemical constituents of ocean-water were used up in building primitive organisms, no material was left for starting new life. We can go further and imagine that the very first forms of life were so helpless and unprotected against somewhat higher organisms, that, even if they should now appear again occasionally somewhere in the ocean they would be immediately eaten up by fish and other marine inhabitants. Thus the existence of life itself may inhibit the appearance of new life, and the only way to start organic evolution anew on the earth may be to kill by the radiation of some superatomic bomb every single living cell on our

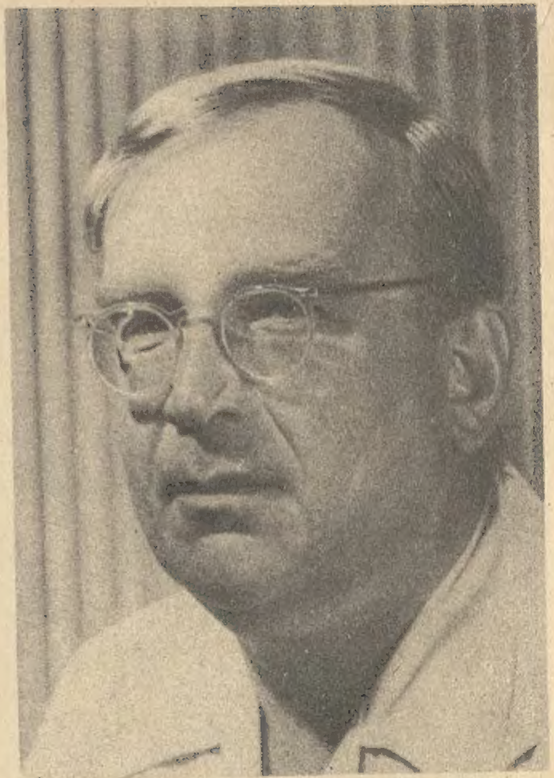
planet, and then to start all over again. If, as it seems to me very likely, the origin of life was really connected with the existence of such a 'missing link' between the inorganic and organic world, the entire problem becomes very difficult to untangle, since, indeed, we are denied any trace of evidence about the original transition process. The problem becomes similar to that concerning the origin of the stars, since astronomers believe now that practically all the stars we see in the sky must have originated some three thousand million years ago at the dawn of the Universe, and that the formation of new stars at the present era is inhibited by the presence of already existing stars. Extinguish all the stars in the sky and new stars will come out, but they will not do it while space is illuminated and heated by stars born a long time ago. But, whereas stars are comparatively simple physical systems, so that the theory of their origin can be conceivably developed without direct observation, we have not at present sufficient theoretical knowledge of living processes to be able to develop a theory of the origin of life without any direct observational support. Thus we are still standing in front of the old problem about the chicken and the egg, wondering which came first: the gene or the protoplasm. Indeed, genes, viruses, and phages which are often called living molecules seem to be the most elementary of all known living organisms, but they cannot live and develop without protoplasm. On the other hand, most features of living protoplasm seem to be conditioned by genes sitting in cellular nuclei. So you see that, even though we have gone a long way in untangling the processes of life, there are still greater distances separating us from its complete understanding. May I conclude with the hope that many of you young people, crowding this lecture room tonight, will be able in the future to make the contributions which will bring us closer to the final goal of understanding the world in which we live."

* * * * * *

The lecture was over, and the Professor was immediately surrounded by a crowd of young students and older men, anxious to ask him questions on various parts of his talk.

"Very, very interesting," thought Mr Tompkins, rising from his chair. "Now I see why so many physicists nowadays forge their cyclotrons into microscopes."

And he walked slowly towards the exit.



Photograph by C. Lehman

THE AUTHOR

George Gamow

George Gamow was born in Russia in 1904, and was educated at the Universities of Leningrad and Göttingen. There he developed the quantum theory of radioactivity; later he did research with Niels Bohr in Copenhagen, and with Rutherford in Cambridge, England. In 1935 he was invited to become professor of Theoretical Physics at the George Washington University in Washington D.C. He is married and has one son.

He is known throughout the scientific world for his pioneering work on the theory of atomic nuclei—and not less for having introduced into it specimens of the characteristic humour which has made his books of popular science so successful.

CYRIL GEORGE HENRY TOMPKINS was born at a comparatively late age, apparently in 1939. He is pretty thoroughly accounted for, genetically and otherwise, in this book, which gives, we may justifiably say, his inside story. Externally he is a bank clerk, married, with one son; he dresses informally, has always had a tendency to baldness, and supports a melancholy moustache.

It was in 1939 that a hard day's work, topped by a Professor's lecture on the problems of modern physics, first led Mr Tompkins to confuse waking and dreaming. He found himself in a small, but expanding universe, where the time scale was rather more obviously relative than usual. More lectures and more dreams gave him a first-hand acquaintance with the velocity of light, the curvature of space, the quanta of energy and the Professor's daughter Maud, whom he married. (See *MR TOMPKINS IN WONDERLAND*) His achievements were officially recognised by the theoretical physicists G. Gamow and E. Teller who, in their article 'On the Origin of Great Nebulae' (*Phys. Rev.* **55**, 654–7, 1939), expressed their gratitude to him for suggesting the topic.

Mr Tompkins might now have seemed to need no more lectures; he had his father-in-law to listen to, morning, noon and night. But nightmares are hard to escape, and Mr Tompkins was always eager to learn. So the Professor got to work again, and Mr Tompkins found himself in another series of microcosmic adventures with Maud, which nearly led to his total annihilation. (See *MR TOMPKINS EXPLORES THE ATOM*) In this latest series of adventures Maud hardly appears. Mr Tompkins had to promise her to steer clear of physics, but he is still curious, and there are other things to learn. Those who are born middle-aged may well raise questions about the facts of life: they have something to catch up with.

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